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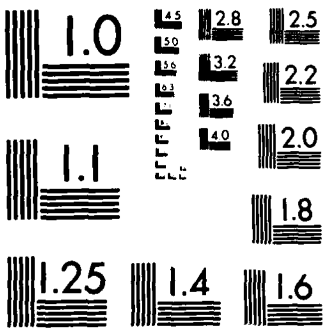

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AD-A171 778

A TRIDENT SCHOLAR PROJECT REPORT

NO. 135

AN INVESTIGATION OF THE HYDRODYNAMIC CHARACTERISTICS OF NON-AXISYMMETRIC BOW SHAPES FOR SUBMARINES

UNITED STATES NAVAL ACADEMY
ANNAPOLIS, MARYLAND
1986

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This report presents the results of an investigation into the resistance and flow characteristics of a series of unconventional bow forms for a body of revolution submarine. The research was conducted as a Trident Scholar research project at the United States Naval Academy. A series of five different bow forms was developed and tested. Three of these bow forms were non-axisymmetric and two were axisymmetric. One non-axisymmetric model served as the baseline and the other two varied in length. The axisymmetric submarine (OVER)

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models were designed and tested to provide a control or benchmark shape typical of current practice. The submerged resistance of the two axisymmetric submarines served as a standard against which the resistance of the non-axisymmetric forms were compared. Fluid flow patterns over the non-axisymmetric bow forms were studied qualitatively by observing tufts attached to the models.

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"AN INVESTIGATION OF THE HYDRODYNAMIC CHARACTERISTICS OF NON-AXISYMMETRIC BOW SHAPES FOR SUBMARINES"

A TRIDENT SCHOLAR PROJECT REPORT

by

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ABSTRACT

This report presents the results of an investigation into the resistance and flow characteristics of a series of unconventional bow forms for a body of revolution submarine. The research was conducted as a Trident Scholar research project at the United States Naval Academy. A series of five different bow forms was developed and tested. Three of these bow forms were non-axisymmetric and two were axisymmetric. One non-axisymmetric model served as the baseline and the other two varied in length. The axisymmetric submarine models were designed and tested to provide a control or benchmark shape typical of current practice. The submerged resistance of these two axisymmetric submarines served as a standard against which the resistance of the non-axisymmetric forms were compared. Fluid flow patterns over the non-axisymmetric bow forms were studied qualitatively by observing tufts attached to the models.

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LIST OF SYMBOLS

C_A	Correlation Allowance
C_F	Frictional Resistance Coefficient
C_P	Prismatic Coefficient
C_{PARA}	Parasitic Resistance Coefficient
C_R	Residuary Resistance Coefficient
C_T	Total Resistance Coefficient
D	Diameter
EHP	Effective Horsepower
F_N	Froude Number
L	Length (ft.)
R_{APP}	Appendage Resistance (lbs.)
R_F	Frictional Resistance (lbs.)
R_N	Reynolds Number
R_{PARA}	Parasitic Resistance (lbs.)
R_R	Residuary Resistance (lbs.)
R_{STRUT}	Strut Interference Resistance (lbs.)
R_T	Total Resistance (lbs.)
S	Wetted Surface (ft^2)
SHP	Shaft Horsepower
PC	Propulsive Coefficient
V	Velocity (ft/s)
C_D	Stimulator Drag Coefficient
ρ	Density ($lb\text{-}sec^2/ft^4$)
ν	Kinematic Viscosity (ft^2/sec)

INTRODUCTION

In order to hear quieter, future enemy submarines, advances in U. S. Navy sonar systems must continue. The detection threshold of a submarine's sonar system (i.e. , the quietest detectable sound which can be identified as a target) is limited by several physical characteristics of the vehicle supporting the sonar system. Major among these characteristics are the noise produced by the hunter submarine's own propulsion system, and the noise created by the turbulent flow over the hunter submarine's bow where sonar systems are usually located. Machinery noise effects can be minimized by placing the sonar transducers as far forward in the submarine as is possible; flow noise effects are strongly dependent upon speed and the smoothness of the flow over the bow.

In general, an increase in transducer area means better sonar performance. Additionally, planar or single degree of curvature transducer arrays are strongly preferred by sonar system designers. Thus, an unconventional bow shape, incorporating large side panels with a single degree of curvature (i.e., cylindrical), appears to be an alternative configuration that could be used to house the next generation of advanced sonar systems in U.S. Navy submarines. While probably improving sonar performance, the effects of the unconventional bow shape on hydrodynamic

performance must be proven satisfactory before such a configuration can be introduced in the fleet.

Responding to the question of hydrodynamic performance, a systematic series of three non-axisymmetric bow-forms, incorporating the above concepts, was designed and tested. The bow forms were of similar cross sectional shape but had varying lengths. The medium length bow served as the baseline. Two axisymmetric bows of conventional shape were also tested as a control group against which the non-axisymmetric bow shapes could be compared. One of the axisymmetric bow models had the same length as the baseline model while the other had the same displaced volume. This was done recognizing the importance of length-to-diameter ratio (L/D) and prismatic coefficient (C_p) on the resistance of submerged submarines.[(1)]* (Appendix A is a glossary of special terms used in naval architecture.)

MODEL DESCRIPTION

The new bow forms incorporated cylindrical arrays on opposite sides of the bow, oriented such that their axes formed a prescribed angle with the submarine's centerline in the horizontal plane. Maximum vertical projected area for the transducers was the driving consideration from the sonar

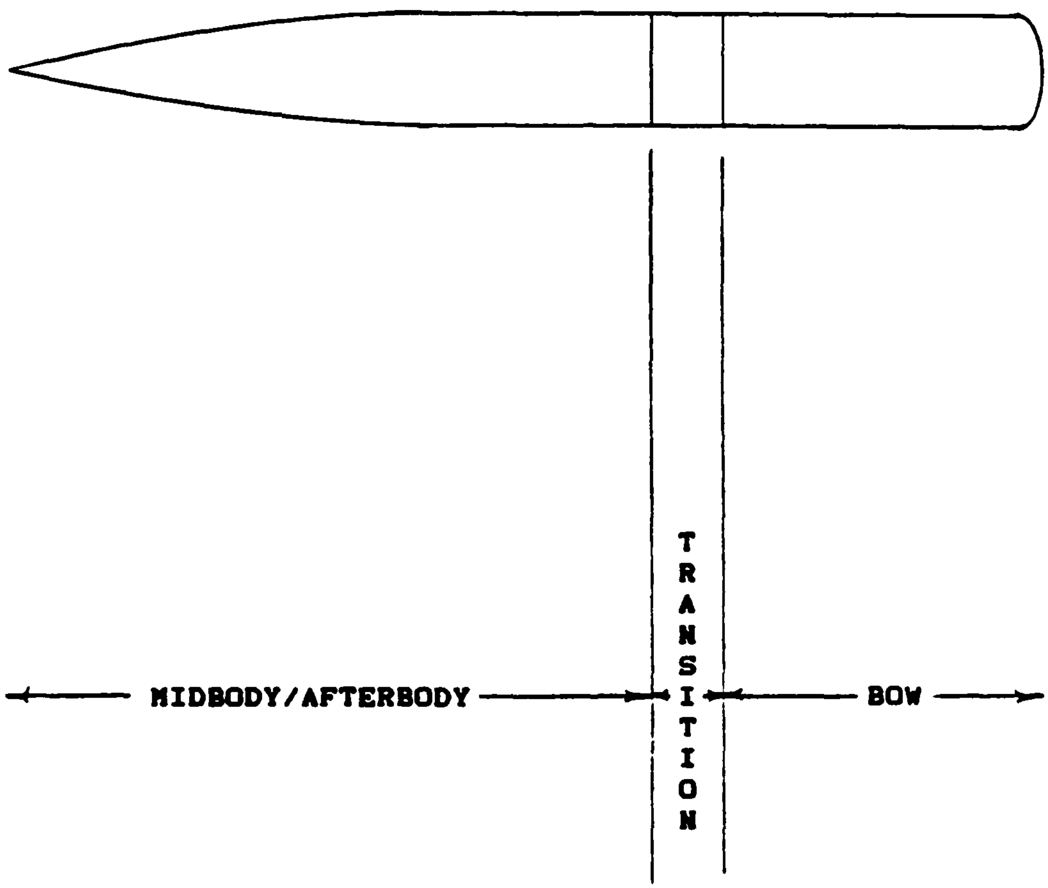
* Raised numbers in parentheses refer to references listed at the end of this report

system analyst's point of view. This meant having as large a diameter as possible for the cylindrical arrays. From the naval architectural point of view, the well documented advantages of axisymmetric body of revolution hull forms with respect to minimum wetted surface per unit length, lightest structural configuration to resist external pressure, and maximum uniformity of flow over the hull and into an axially mounted propeller had to be considered.

With the help of Capt. Harry Jackson, USN (ret.), a well known submarine design consultant, these design requirements led to the development of a submarine hull consisting of three identifiable segments as shown in Figure 1. These are:

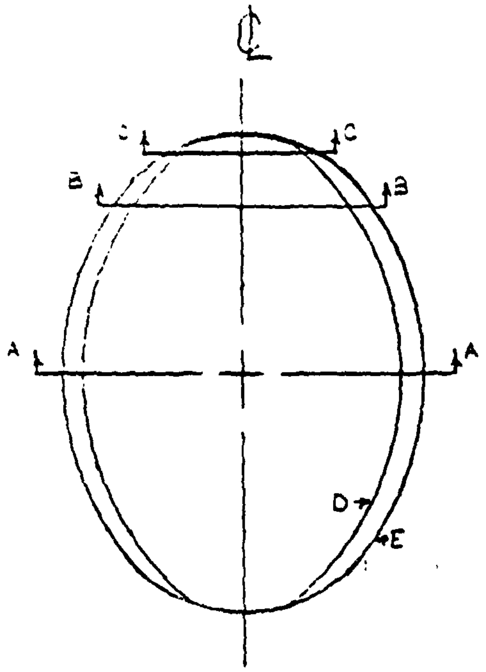
(1) a bow segment which contains the hypothetical sonar transducer arrays - right circular cylindrical surfaces of a given length and with maximum radius and vertical extent, consistent with overall hull fairness. Cross sections of the bow segment were roughly elliptical in shape with a vertical major axis. The forward end of the bow section was faired by revolving the forward station of the bow about a vertical axis. Figure 2 shows typical transverse vertical sections (stations) and typical horizontal sections (waterlines) for a bow segment.

(2) a transition segment which smoothly blends the

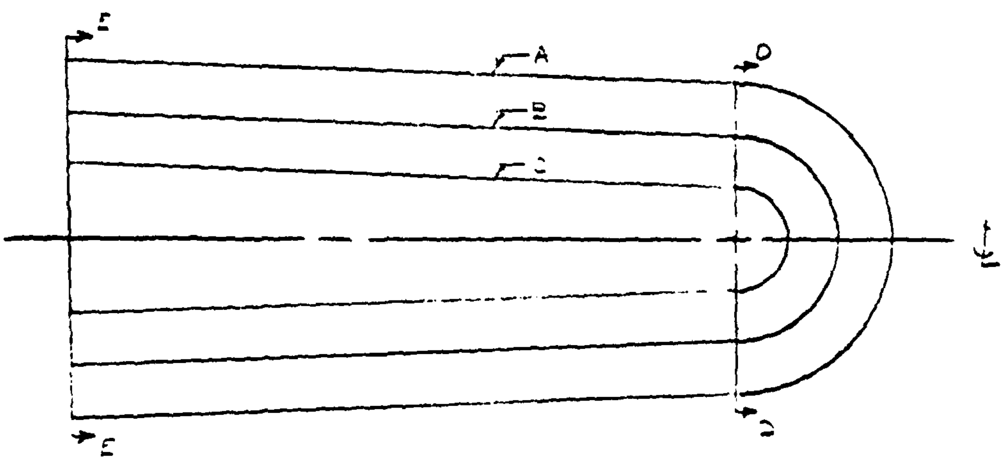


HULL SEGMENTS

FIGURE 1



STATIONS



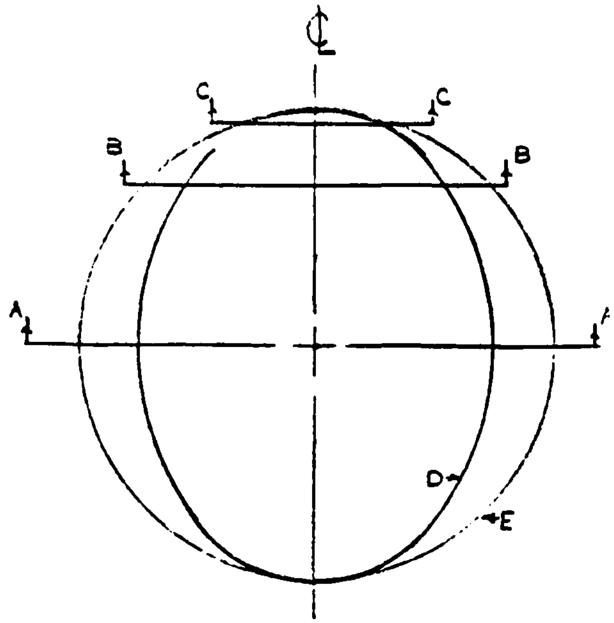
WATERLINES

BOW SEGMENT
FIGURE 2

elliptical cross sections of the bow segment into the circular cross sections of the mid and afterbody segment. A compromise was required between a long transition segment to maximize hydrodynamic smoothness of flow (to minimize pressure drag increases), and a short transition segment to minimize submarine size (and thus cost) and wetted surface area (to minimize frictional resistance increases). Smoothness of flow in the area of the transition has operational implications if torpedo tube shutter doors are to be located at or just aft of the transition on a prototype submarine. Typical stations and typical waterlines for the transition segment are shown in Figure 3.

(3) a midbody/afterbody segment which is a pure body of revolution. A purely cylindrical parallel middle body is faired into an afterbody whose shape is a paraboloid of revolution. The proportions of the midbody/afterbody segment were chosen to approximate current submarine design practice.[8] Figure 4 shows typical stations and waterlines of the midbody/afterbody segment.

A series of original computer algorithms was developed to define the geometries of the three segments for the purposes of creating hull lines drawings from which physical test models could be built. The BASIC programs incorporating these algorithms are given in Appendix B.



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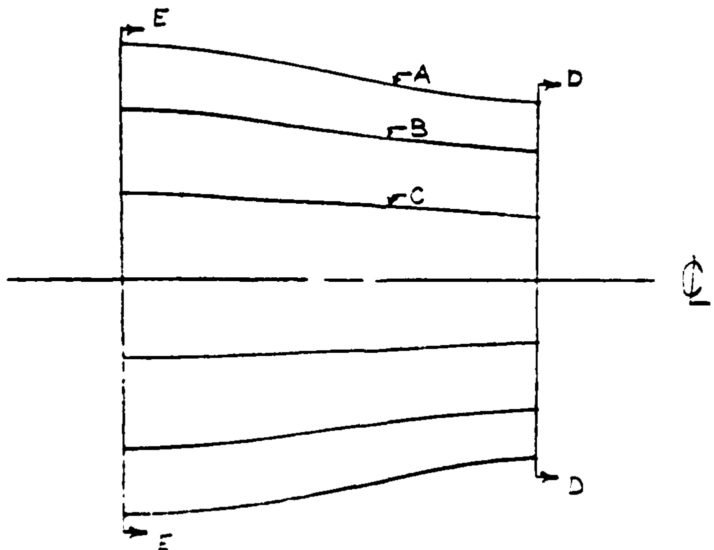
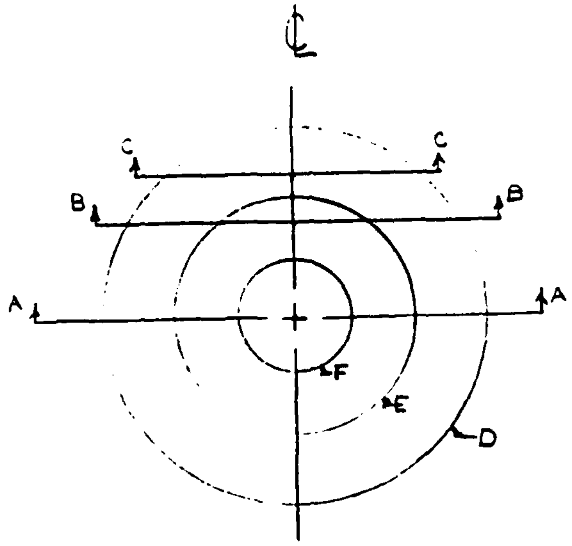


WATERLINES

TRANSITION SEGMENT

FIGURE 3



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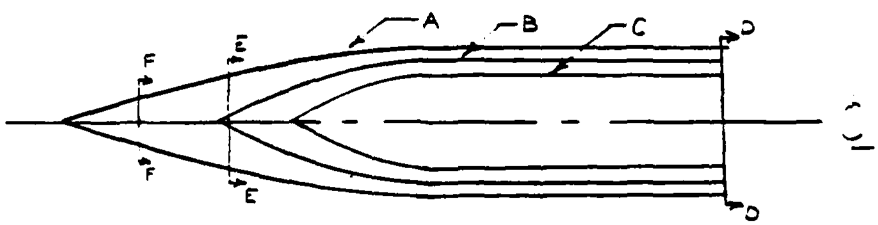


WATERLINES

MIDBODY/AFTERBODY SEGMENT

FIGURE 4

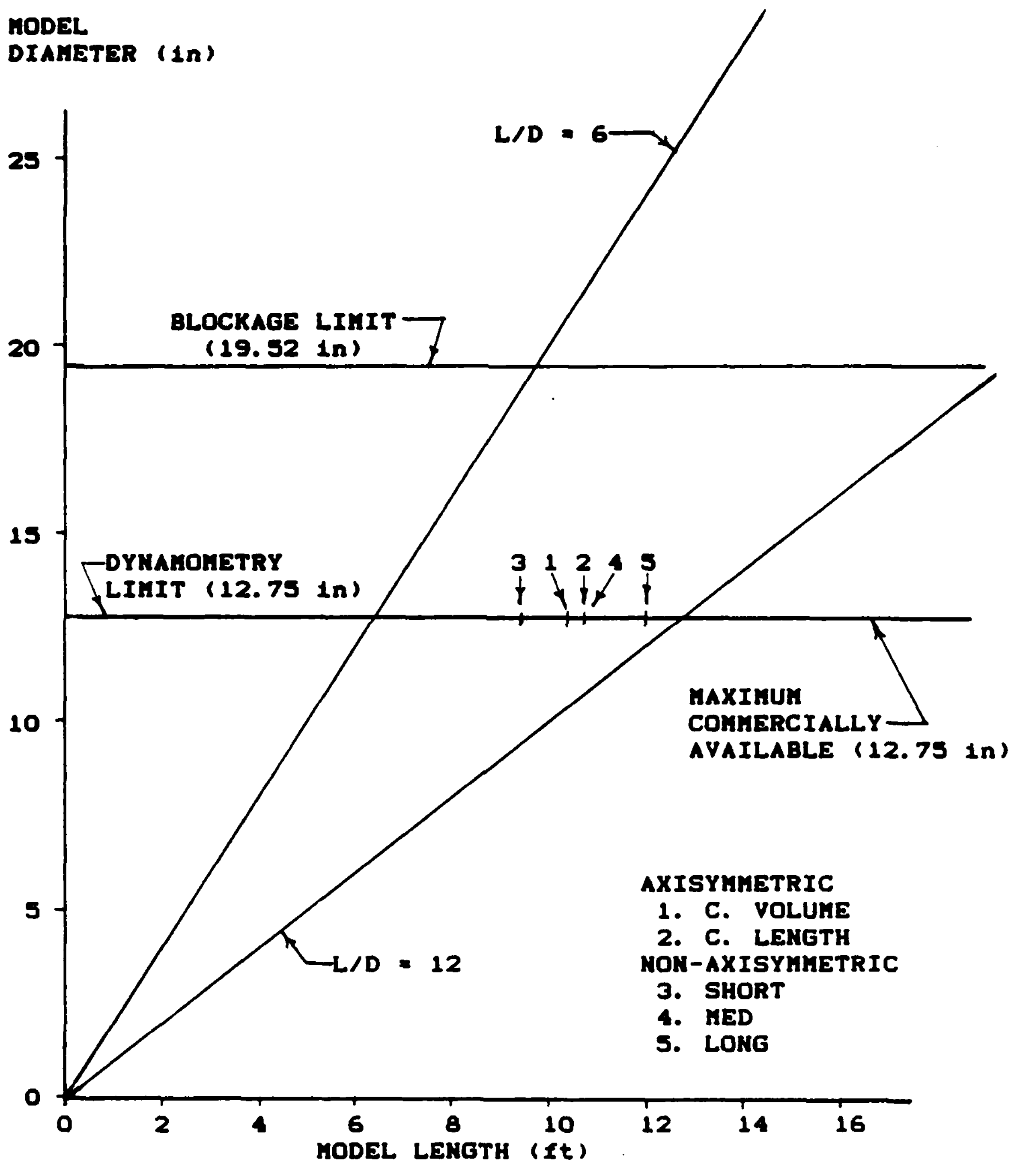
The trade-off between increased array length for sonar performance and the degradation to hydrodynamic performance, if any, became the central issue to be studied by means of the previously discussed systematic series of bow shapes. A baseline array length to projected height ratio of 2.25 was recommended by Capt. Harry Jackson, USN (ret.) on the basis of prior sonar array configuration analysis.[3] Two variations of the baseline array length were selected as well. The longer had an array length to projected height ratio of 3.50, while the shorter had a ratio of 1.00. For all three members of the series, cross section shape and nose fairing geometry were similar - as shown in Figure 2. Also, except for minor slope changes to maintain local fairness at its interface with the bow segments, the transition segment was identical for all three bow forms.

The overall geometric proportions of the submarine models to be tested were chosen on the basis of historic trends published in unclassified literature [2,4,5] such that the slenderness of the submarine measured by the length to diameter ratio (L/D), was representative of good practice but without reference to any specific submarine. In addition to this criterion of having realistic proportions, the mechanical configuration of the apparatus and test facilities limited the size and shape of the actual test models.

Since the models were to be tested in the submerged

condition to compare the hydrodynamic characteristics of the various bow shapes, it was decided that the axisymmetric midbody/afterbody segment, in which the support and measurement mechanism would be housed, would be used for all bow shape variations. The cylindrical midbody was made free flooding to minimize the hydrostatic forces and moments acting on the towing strut. This was possible because the resistance measurement apparatus is waterproof and can withstand extended periods of submergence. To facilitate model construction, extruded aluminum tubing (commercially available) was selected for the model cylindrical midbody. Availability, weight, and resistance to corrosion were primary factors leading to the selection of aluminum (over steel or PVC) as the material for the midbody.

The maximum diameter that could be used and remain within the five percent blockage criterion for resistance testing in the Naval Academy's 380 foot towing tank was 19.52 inches. A twelve inch inside diameter was required in order to house the required dynamometry (this corresponds to a 12.75 inch outside diameter for standard aluminum pipe). The maximum diameter available for commercially available aluminum tubing was 12.75 inches. A summary of all model sizing criteria are plotted versus model length and diameter in Figure 5. Points representing the five models that were ultimately designed, fabricated and tested are plotted on this figure as well.

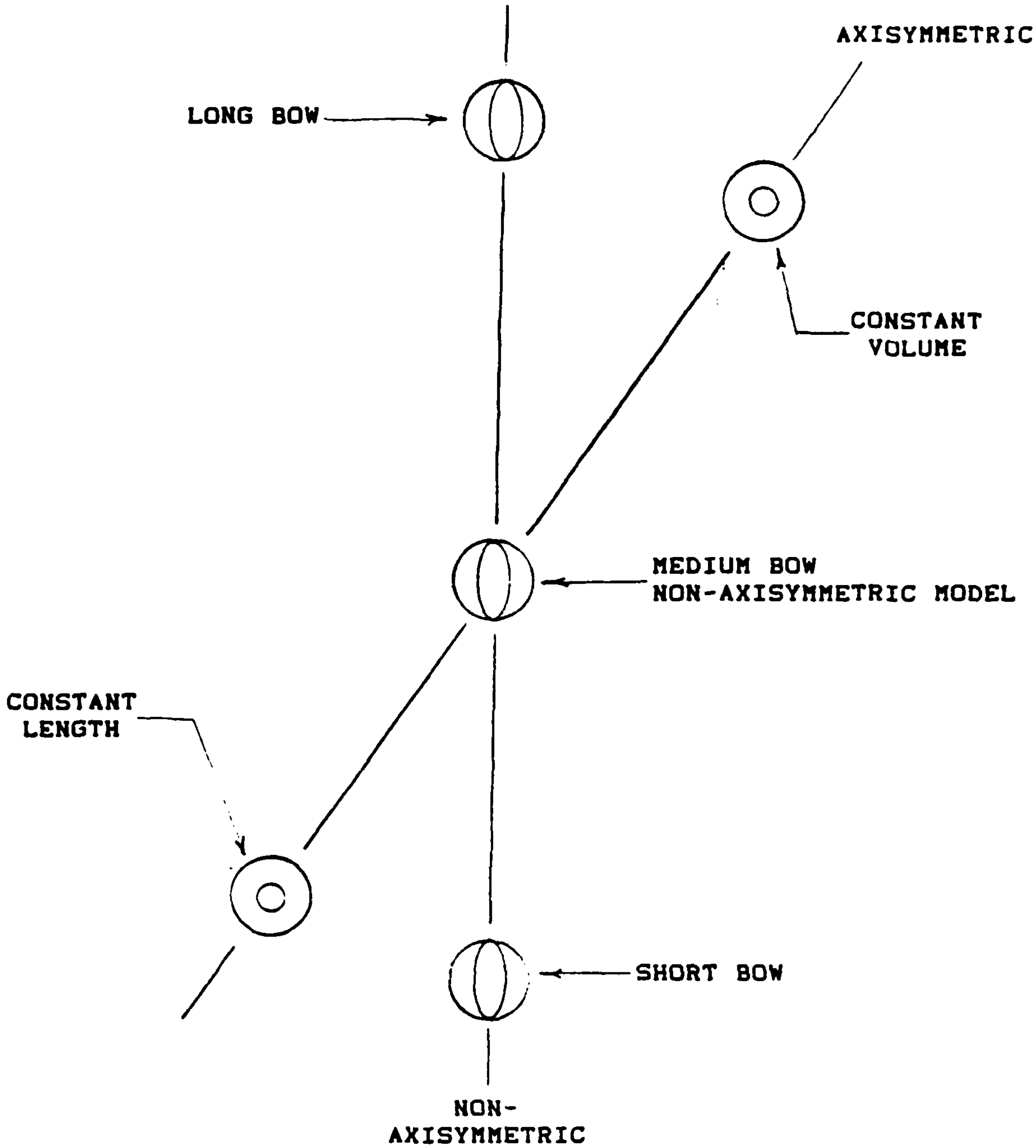


MODEL SIZING CONSTRAINTS

FIGURE 5

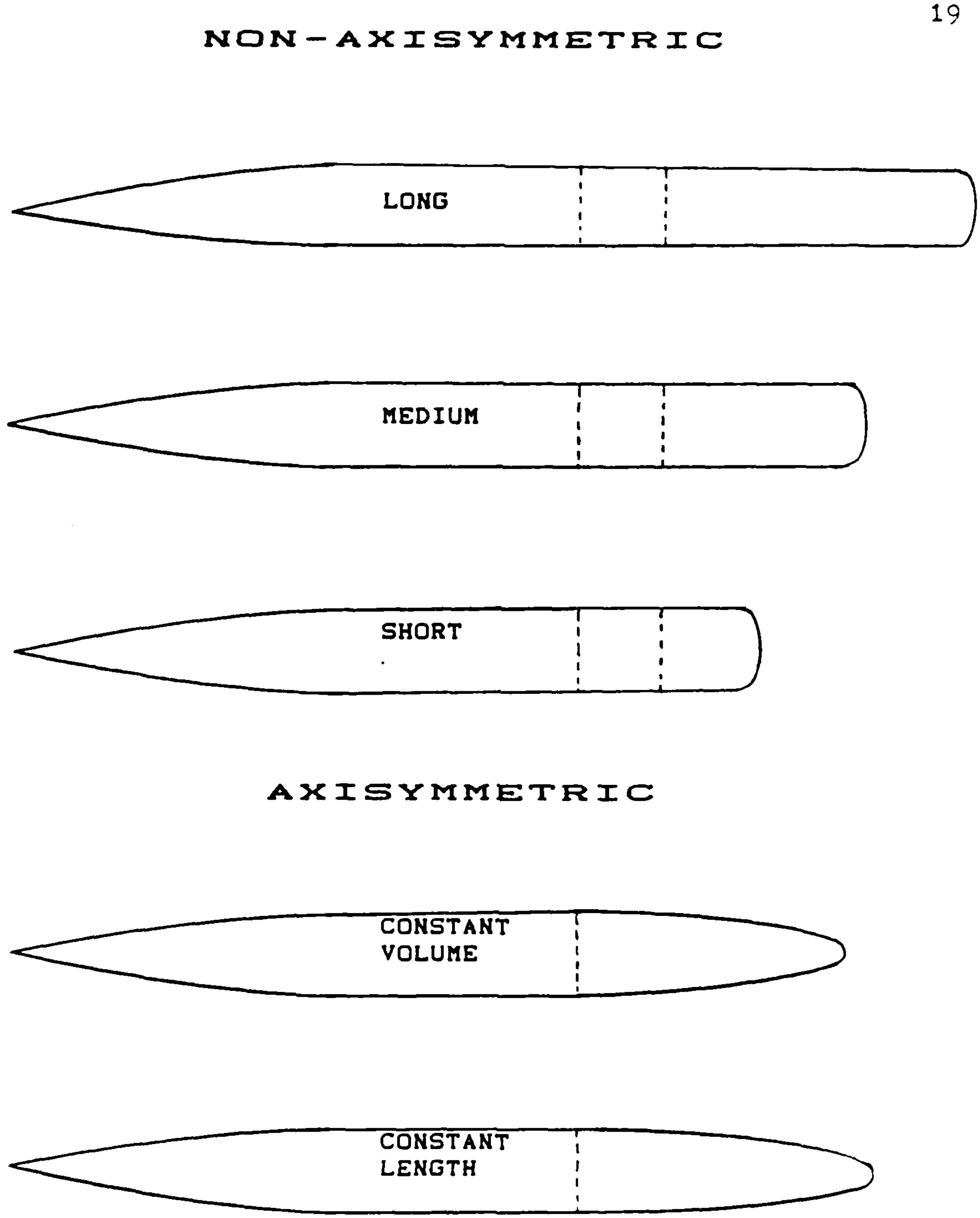
It was decided that two axisymmetric conventionally shaped bow forms would be tested in addition to the non-axisymmetric bow shapes. An important consideration was the availability of data on the axisymmetric forms, allowing the non-axisymmetric bow data to be compared to known standards of similar overall geometry. One of the axisymmetric models was designed such that it had the same length as the baseline non-axisymmetric model. This gave the axisymmetric form the same length to diameter ratio as the baseline. The second axisymmetric form was designed such that it had the same displaced volume as the baseline. This would allow us to study the effects of the new shape compared to an axisymmetric shape having an equal volume. The axisymmetric bow shapes utilized the same midbody/afterbody segment that the non-axisymmetric bows used. This helped to maintain consistency among all five model tests which were conducted over a time span of five months. The complete series of models tested is shown in matrix form in Figure 6. Figure 7 gives a scale profile view of each submarine tested and Figure 8 is a table of model characteristics. Tabulated values of wetted surface and volume do not include any contributions from appendages.

In order to increase yaw and pitch stability of the submarine models, the afterbody segment was fitted with a set of four tail fins. The tail fins increased the stability of the submarine in much the same way as the fins on a rocket or fletching on an arrow help to maintain directional



SUBMARINE MATRIX

FIGURE 6



SUBMARINE COMPARISON

FIGURE 7

TRIDENT SCHOLAR PROJECT
SUBMARINE CHARACTERISTICS

MODEL	NON-AXISYMMETRIC			AXISYMMETRIC	
	LONG	MEDIUM	SHORT	C. LEN	C. VOL
L (stern) (ft)	3.82	3.82	3.82	3.82	3.82
L (pmb) (ft)	3.19	3.19	3.19	3.47	3.19
L (bow) (ft)	4.99	3.64	2.34	3.36	3.36
LOA (ft)	12.00	10.66	9.366	10.66	10.37
S (stern) (ft^2)	9.36	9.36	9.36	9.36	9.36
S (pmb) (ft^2)	10.65	10.65	10.65	11.59	10.65
S (bow) (ft^2)	13.56	9.70	5.97	9.54	9.54
S (total) (ft^2)	33.57	29.71	25.95	30.49	29.55
Vol (stern) (ft^3)	2.104	2.104	2.104	2.104	2.104
Vol (pmb) (ft^3)	2.828	2.828	2.828	3.077	2.828
Vol (bow) (ft^3)	3.133	2.304	1.577	2.304	2.304
Vol (total) (ft^3)	8.065	7.236	6.509	7.486	7.236

FIGURE 8

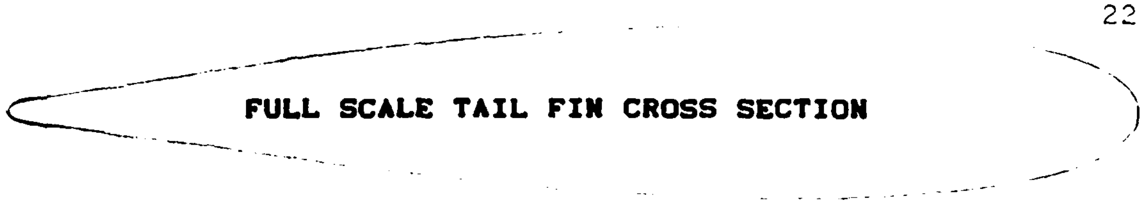
stability (i.e., by increasing the resistance at the stern). Figure 9 is a diagram showing the afterbody segment with the tail fins appended. The four fins were symmetric airfoil shapes with a thickness to chord ratio of 0.15. Their projected area was established according to early stage submarine design practice.[3] In order to maintain consistency, the same tail fin configuration was used in every model test.

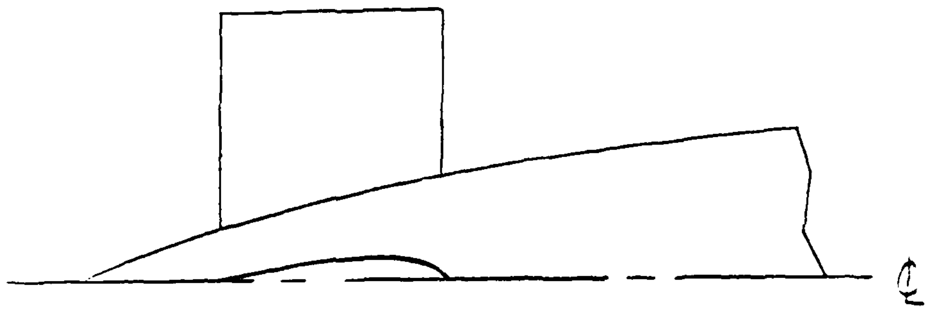
TESTING METHOD

Whenever scale models are used to predict the performance of a ship, the problems attendant to the lack of perfect modeling - i.e., simultaneous satisfaction of geometric, kinematic, and dynamic similitude - cause the investigator to make hard engineering choices as to the best way to proceed. In the present investigation, dimensional analysis and knowledge of the fluid mechanics of submerged body resistance helped the author to make these decisions. It is accepted practice in model testing to nondimensionalize the resistance by using resistance coefficients defined as follows:

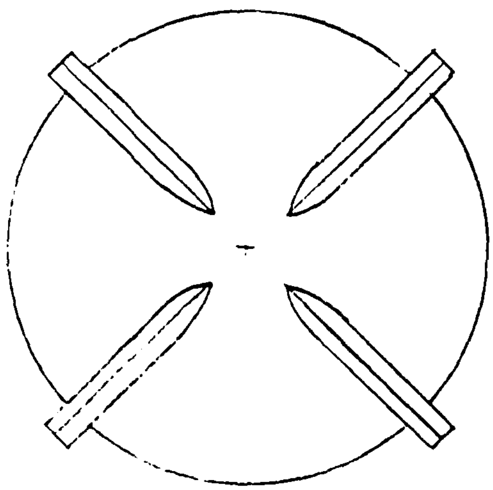
$$C_x = \frac{R_x}{1/2\,\rho S V^2} \qquad (1)$$

Where R_x is the resistance force to be nondimensionalized, C_x is the corresponding resistance coefficient , ρ is the density of the fluid in which the submarine is traveling, S is the wetted surface of the submarine (not including any





45° PROFILE VIEW



STERN VIEW

SUBMARINE TAIL FINS

FIGURE 9

appendages), and V is the velocity of the submarine. The resistance coefficient is a dimensionless number that can be used in relating resistance values of geosims (geometrically similar shapes).

A submarine model can be tested in a number of ways. Two facility alternatives are the towing tank and the wind tunnel. In a wind tunnel, the submarine model would have been tested in air at a speed that makes the Reynolds numbers of the model and the prototype equal. The Reynolds number is the ratio of inertia force to the viscous force. It can be calculated using the following formula:

$$R_N = \frac{V \cdot L}{\nu} \qquad (2)$$

The Reynolds number is important because when the model and the ship (both deeply submerged) travel at equal Reynolds numbers, the total resistance coefficient of the model ($C_{T/M}$) is equal to the total resistance coefficient of the ship ($C_{T/S}$). Physically this means that the boundary layer geometry on both the model and the prototype would be similar.

The primary drawback of wind tunnel testing is the size constraint placed on the model in order to avoid blockage effects within the Naval Academy wind tunnels. Because of the model's size, the air speed in the wind tunnel must be very high in order to meet the Reynolds number criterion. As an example, if the scale ratio were 100 (L_S/L_M = 100),

the model in a wind tunnel must travel at approximately 1200 times the corresponding speed of the ship. This would place the model of a typical submarine above the Mach 0.25 range which introduces compressibility effects, another complication that would require careful attention.

If a Reynolds scaled test were performed in a towing tank, the model would be required to be run at a speed approximately equal to the speed of the ship times the scale ratio (using the above example, this would correspond to 100 times the corresponding speed of the ship). At this speed, the resistance of the model is nearly equal to the resistance of the ship. Even if the power required to do this were available, such extremely high speeds are not achievable in the Naval Academy Hydromechanics Laboratory 380 foot towing tank (or any other).

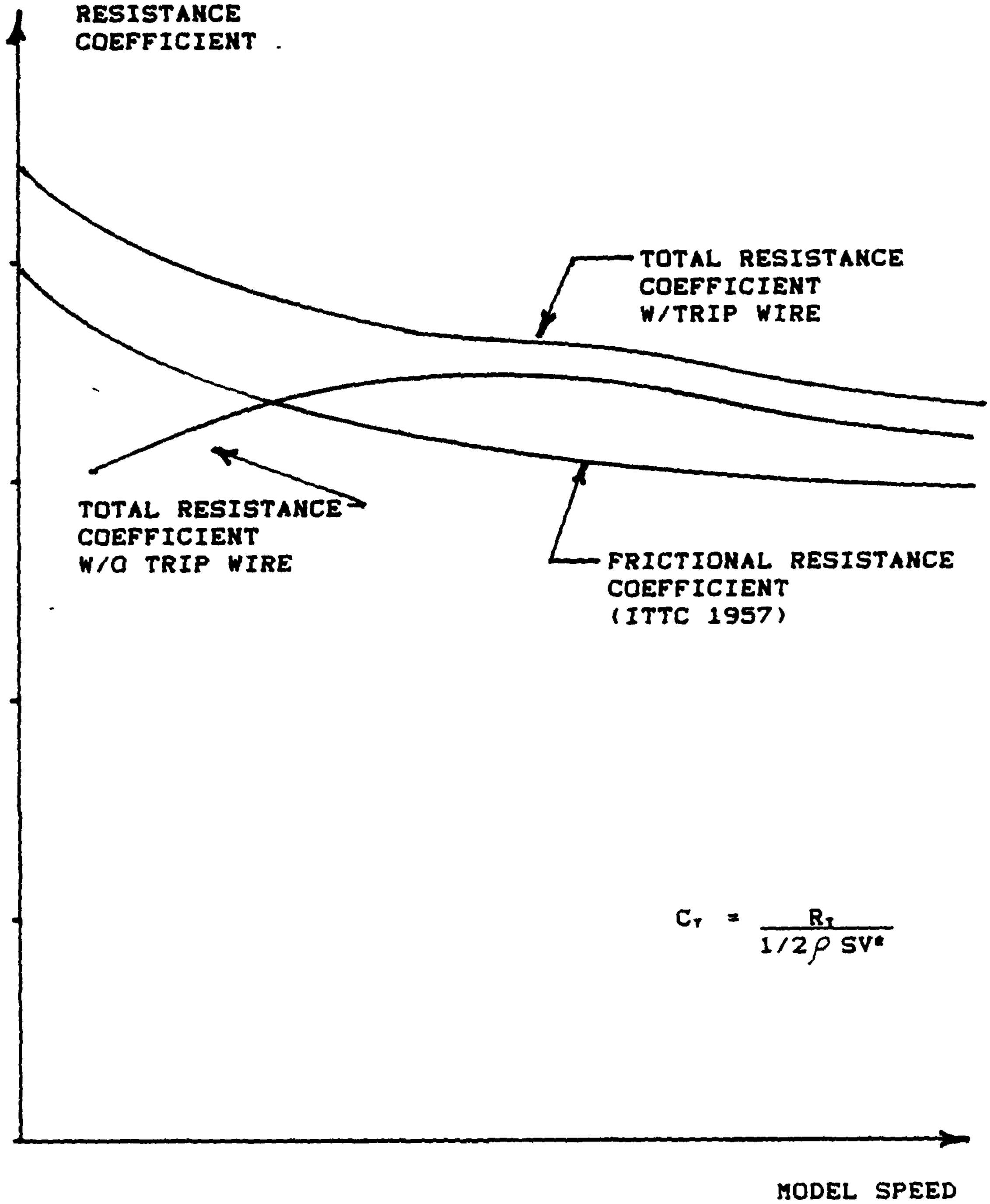
The most practical alternative is to perform a low speed test in a towing tank similar to those done on surface ships. In this type of test, the total resistance of a submarine (R_T) is broken down into two parts: the frictional resistance (R_F) and the residuary resistance (R_R) (also called form resistance). The residuary resistance coefficient (C_R) for a deeply submerged submarine is assumed to remain constant over the speed range of the ship.[1,6] By deeply submerged, it is meant that the submarine is far enough below the free surface that the pressure field created by the submarine's forward speed will not generate waves on the free surface. The lower limit on

model speed is determined by the nature of the viscous flow over the model. When the model travels at these slower speeds, there will probably be laminar flow over a portion of the hull. Because the flow over a full scale submarine is turbulent, the model must be artificially stimulated in order to produce turbulent flow (for dynamic similarity). The type of stimulation most often used on submarine models is a trip wire. A trip wire is a continuous loop of wire (e.g., piano wire) wrapped around the circumference of the submarine model near the bow. The trip wire disturbs the fundamentally unstable laminar flow into becoming turbulent by destroying the very smooth, layered flow along the bow of the model. Once tripped, the more stable turbulent flow is presumed to prevail from the disturbance aft. Trip wire sizing and placement are empirical and based on experience.[7]

Figure 10 gives an example of the variation of the total resistance coefficient, with and without a trip wire, versus model speed. The effect of the laminar flow on the unstimulated model can be seen through the lower resistance values at the slower speeds. The residuary resistance coefficient can be obtained using the following equation:

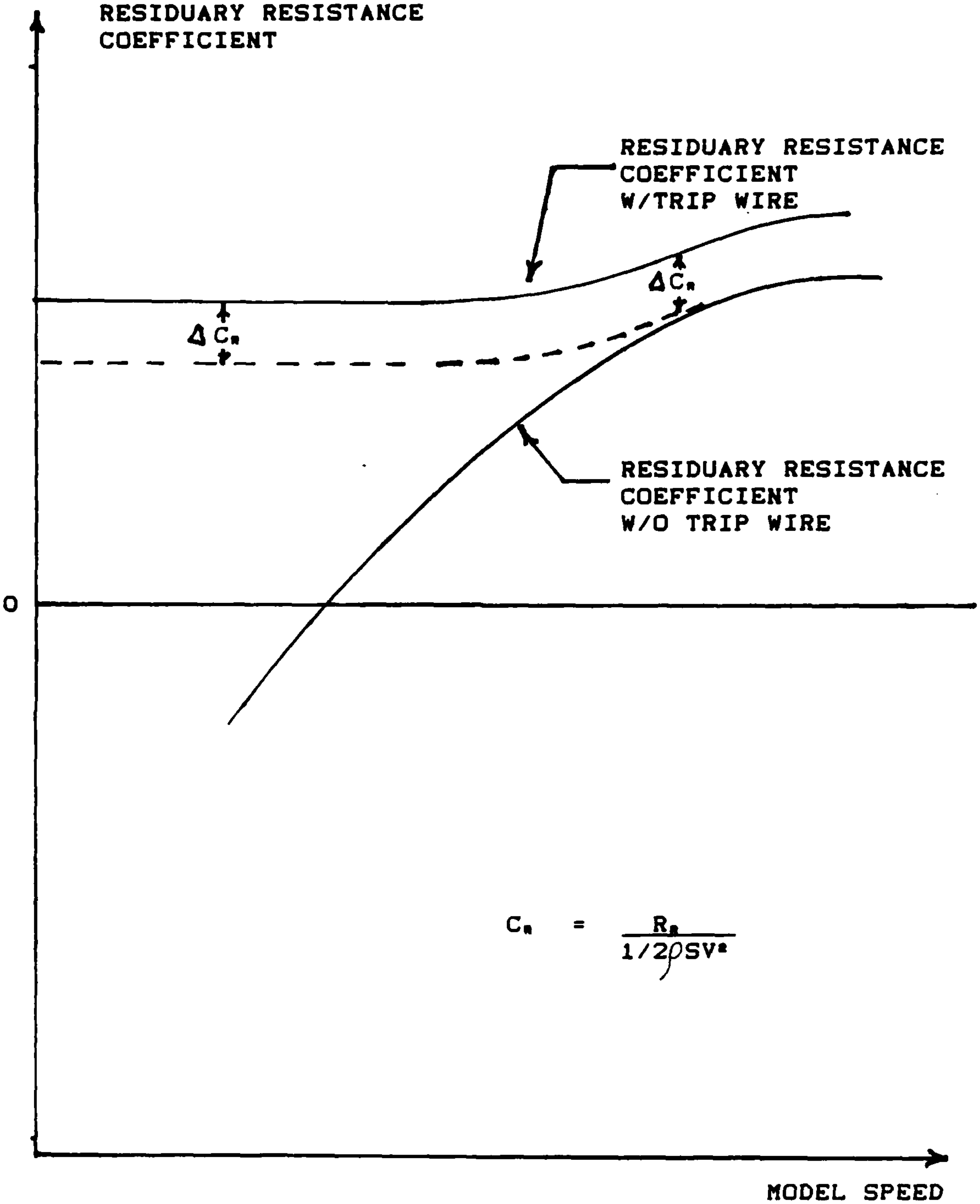
$$C_R = C_T - C_F \qquad (3)$$

A typical plot of C_R versus model speed can be seen in Figure 11. The frictional resistance coefficient (C_F) is relatively easy to obtain. The equation most often used in



TOTAL RESISTANCE
COEFFICIENT

FIGURE 10



$$C_R = \frac{R_R}{1/2\rho S V^2}$$

RESIDUARY RESISTANCE COEFFICIENT

FIGURE 11

ship model testing is the ITTC 1957 Model - Ship Correlation Line (ITTC stands for the International Towing Tank Conference). This is a well known standard for calculating the turbulent frictional resistance coefficient of both surface ships and submarines. The ITTC frictional coefficient can be calculated using the following formula:

$$C_F = \frac{0.075}{(\log_{10} R_N - 2)^2} \qquad (4)$$

ITTC 1957 is the standard used by David Taylor Naval Ship Research and Development Center (DTNSRDC) in the testing of submarine models. The effect of the laminar flow on a model can be observed at the lower speeds. If the model is experiencing laminar flow its frictional resistance is significantly less than it would be if it were turbulent. In such a case, Equation 3 may yield a negative C_R if the frictional resistance coefficient presumes turbulent flow. A model speed corresponding to some arbitrarily selected Reynolds number is the method by which the low end of the speed range is determined. The hump in the C_R curve at the highest speeds tested is thought to be due to the proximity of the model to the surface. Submarine model tests at DTNSRDC show a similar phenomenon in the same dimensionless speed range. If the submarine model were towed at an infinite depth, there should be no wave hump in the curve[1]. The trip wire resistance coefficient (ΔC_R) is the difference between the two C_R curves where they are parallel to one another at the higher speeds. This difference (ΔC_R)

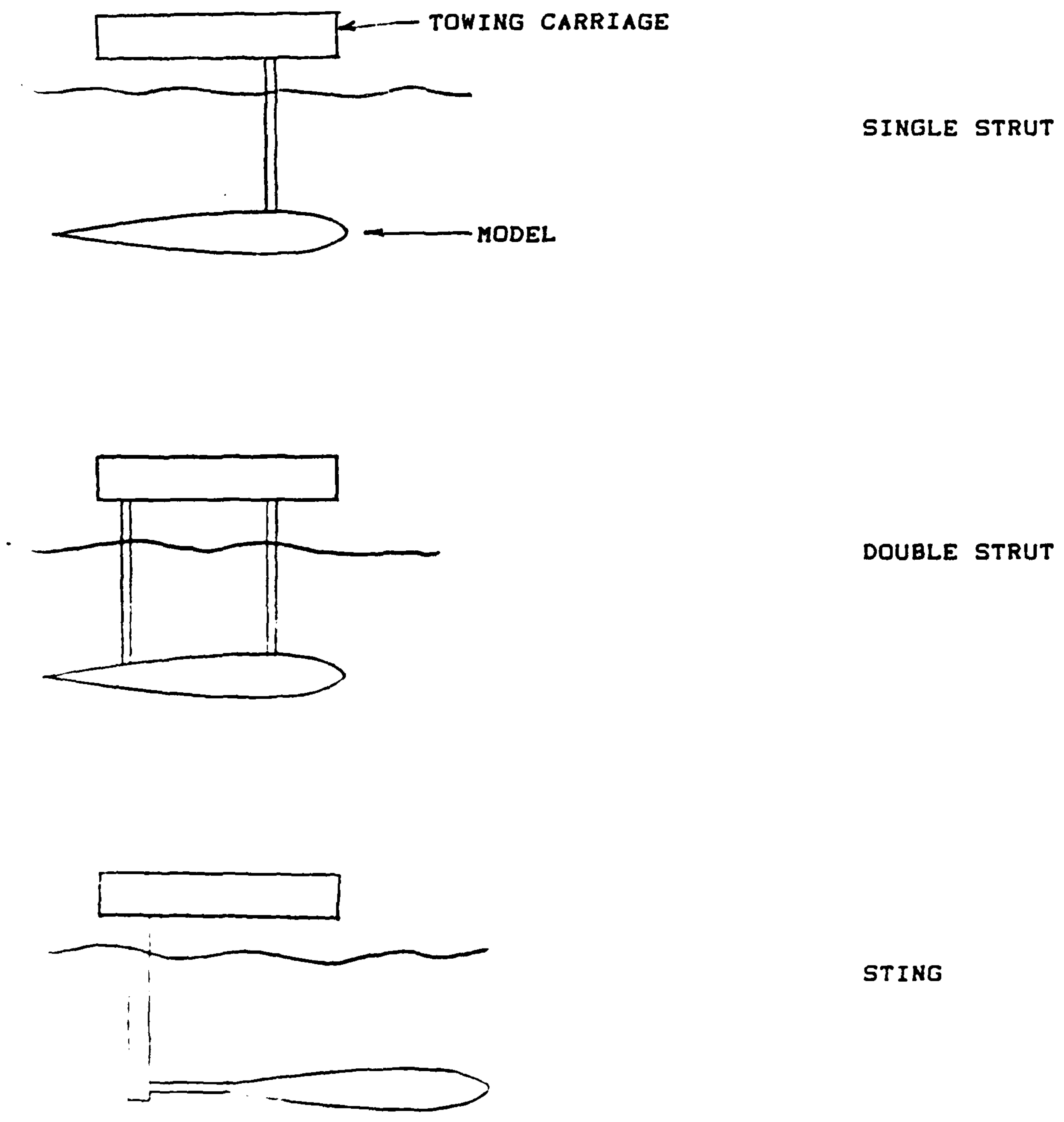
can be extrapolated to the lower speeds in order to obtain a value for the residuary resistance coefficient (C_R) or form drag factor.

SETUP & DYNAMOMETRY

The Naval Academy Hydromechanics Laboratory had never tested a submarine model of the size described above. This fact meant that the submarine test procedure and apparatus had to be developed. There are three accepted methods for testing submarine models in a towing tank. The methods differ in the way in which the submarine model is restrained at the desired submerged attitude. These methods employ as model restraint a single vertical strut, a double vertical strut, or a horizontal strut called a sting. The first method consists of a single supporting strut extending from the towing carriage to the submerged model. The dynamometry for this method is mounted on the submarine end of the strut. The placement of the strut along the length of the model is critical. The further aft the strut is attached, the more unstable in yaw and pitch the model is likely to be; the further forward the strut is placed, the larger the portion of the submarine that experiences disturbed flow caused by the strut wake. The second method, employing two vertical struts, is similar to the single strut except that there is a second strut that extends vertically from the carriage to the model aft of the first strut. The major advantage of this method is the increased yaw and pitch

stability of the model. The disadvantages of this method are the probability of locked in forces between the two struts, the added complexity of the towing rig, and the added disturbance of the second strut. The third method is the sting method. This method utilizes a single horizontal support that enters the submarine model through the stern. The advantage of this method is that there is no disturbance of the flow over the forward portion of the submarine. The disadvantages of this method are the large yaw and pitch moments that the support must withstand and the possible distortion of the submarine model shape where the sting enters the model. Diagrams describing these three methods can be found in Figure 12. An analysis of the characteristics of the three methods listed above, and the expressed preference of DTNSRDC, the U.S. Navy's premier submarine test facility, led to the selection of the single strut method.

Because we chose the single strut towing method, the pitch and yaw stability of the model were of prime importance. Using estimated values for the resistance of the model, the size of the strut and the support/alignment rig that connects the strut to the towing carriage were calculated. The towing point was placed as far forward in the midbody region as possible so as to minimize the Munk moment (the hydrodynamic yawing moment on the submarine). The Munk moment was estimated for the proposed towing point using an accepted empirical method that assumes the model to



SUBMARINE TOWING METHODS

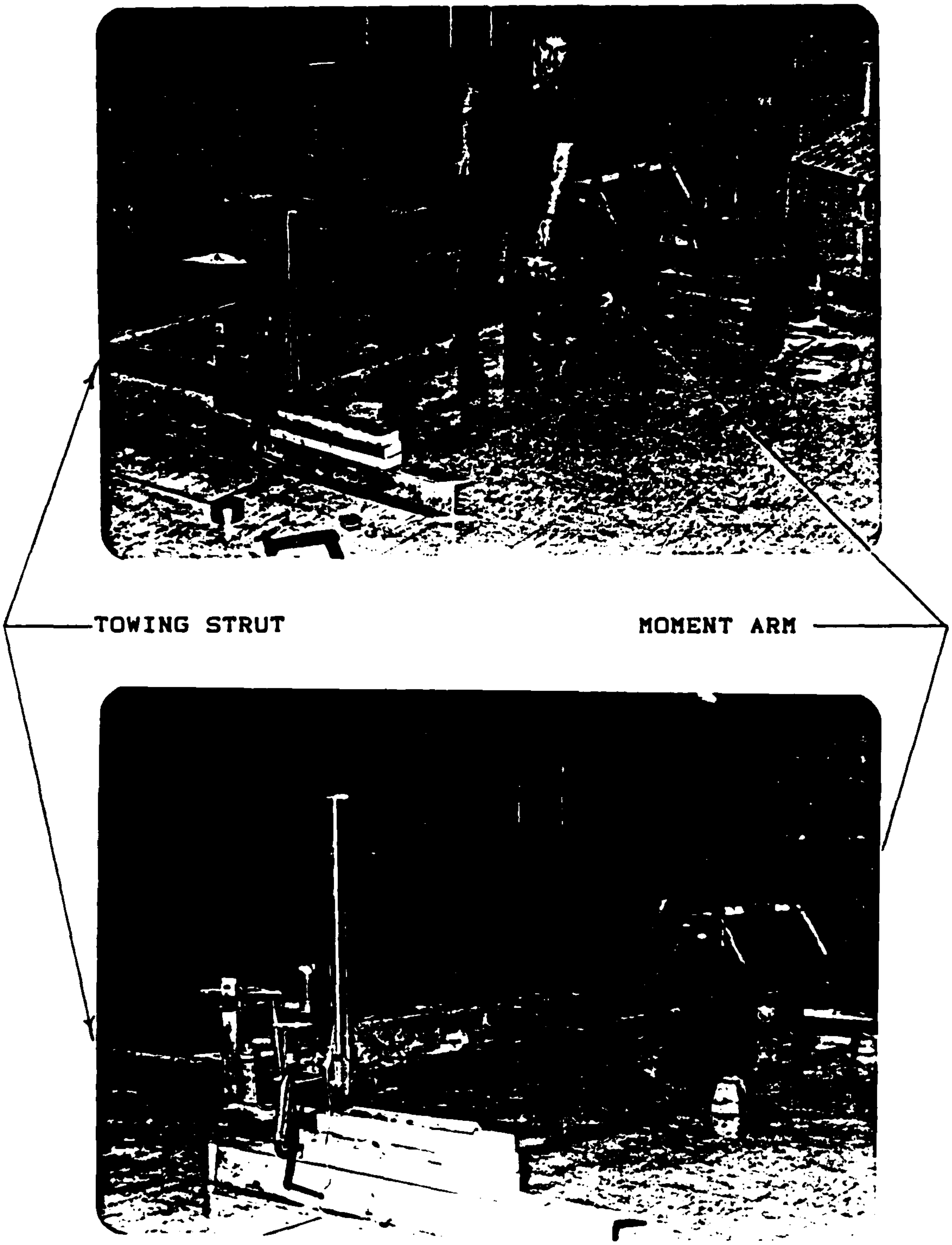
FIGURE 12

be an ellipsoid of revolution with the same principal dimensions as the actual model. The towing strut was statically tested to determine its torsional rigidity (Figure 13). The predicted Munk moment at a model speed of twenty feet per second was only 12.6 percent of the measured torsional rigidity. A diagram showing the towing rig can be found in Figure 14.

Because of the estimated magnitude of the pitch moment produced by the model on the towing strut, it was determined that a single force block would not provide sufficient pitch restraint. A set of two one hundred pound force blocks were connected to each other and the towing strut by a common flange, and their output summed to measure the resistance force. A diagram showing the dynamometry arrangement can be found in Figure 15. Locked in forces between the force blocks were accounted for by performing an in-place calibration. That is, the summed electrical output of the force blocks was measured against variable force after the entire submarine was assembled and mounted on the towing strut.

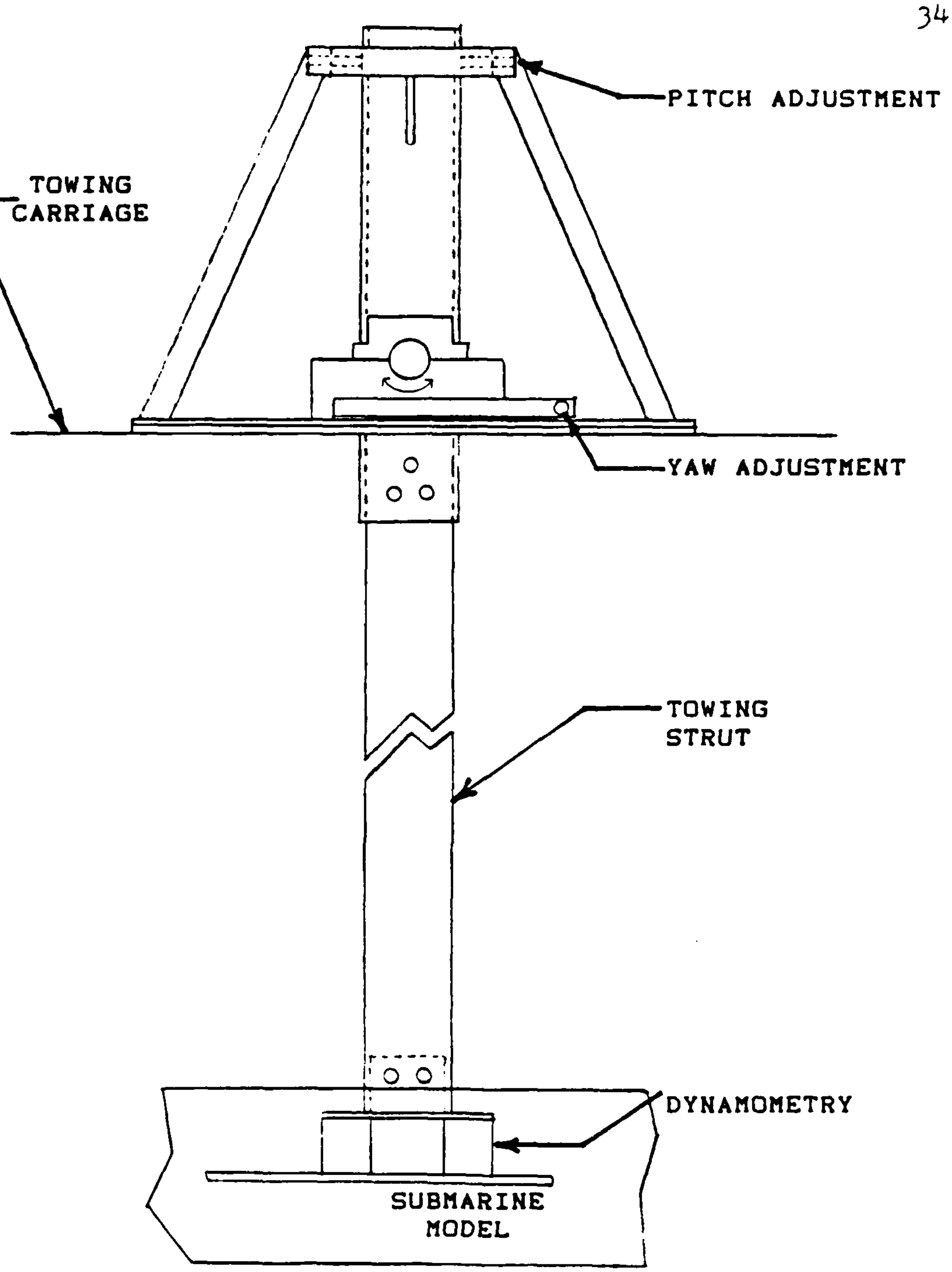
TEST PROCEDURE

All model tests were performed at the Naval Academy Hydromechanics laboratory (NAHL). The models were tested in the 380 ft. long towing tank (Figure 16). After the towing rig was mounted in the low speed carriage (capable of obtaining 25 fps), the submarine model being tested was



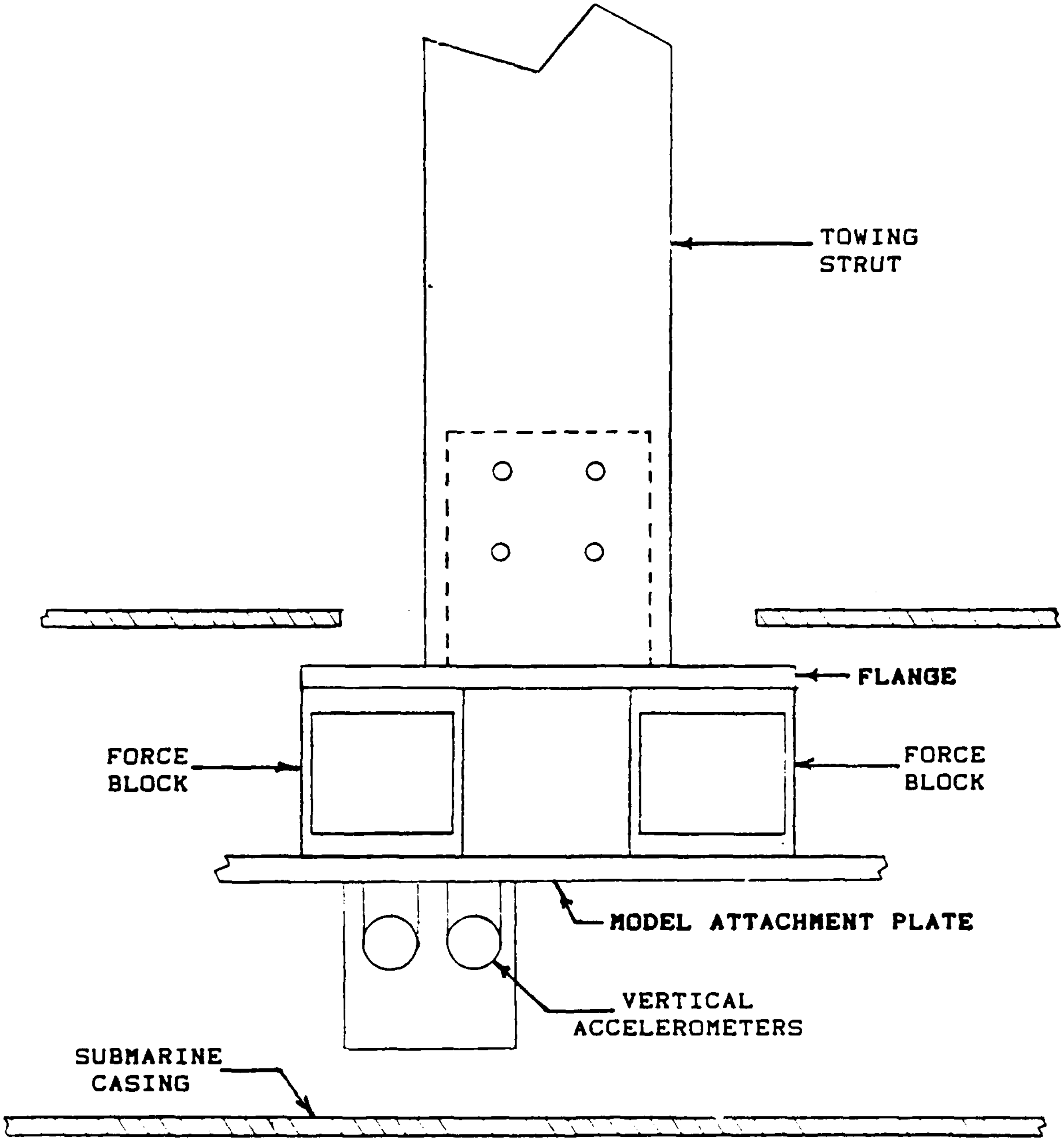
TORSIONAL RIGIDITY TEST

FIGURE 13



TOWING RIG

FIGURE 14



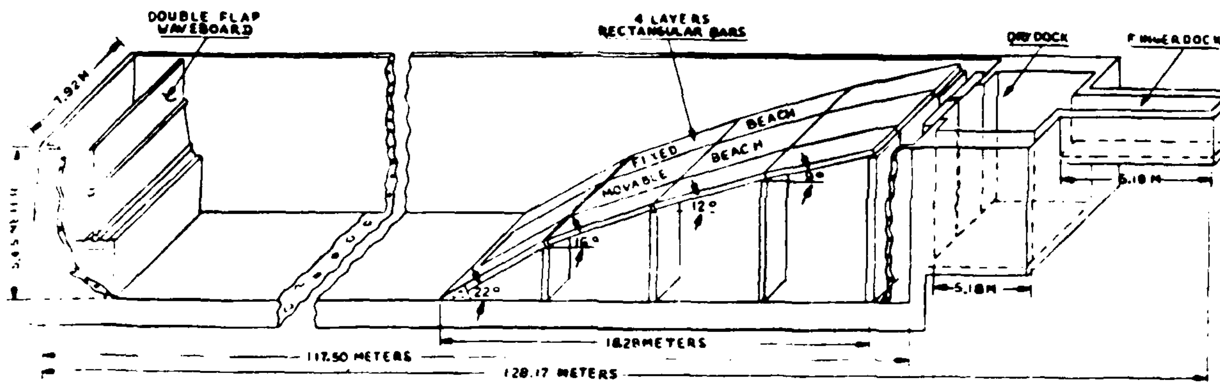
DYNAMOMETRY

FIGURE 15

U. S. NAVAL ACADEMY HYDROMECHANICS LABORATORY
ANNAPOLIS, MARYLAND 21402
TELEPHONE: (301) 267-3361

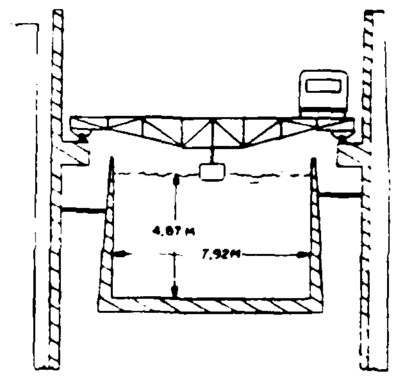
U.S.A.

128m HIGH PERFORMANCE TOWING TANK (1979)



380 FOOT TANK AND WAVEMAKER

U.S. NAVAL ACADEMY



DESCRIPTION OF CARRIAGE:
1) high speed - box girder, supported on round way bearings or rulon slippers
2) low speed - supported on round way bearings (towed by high speed carriage)

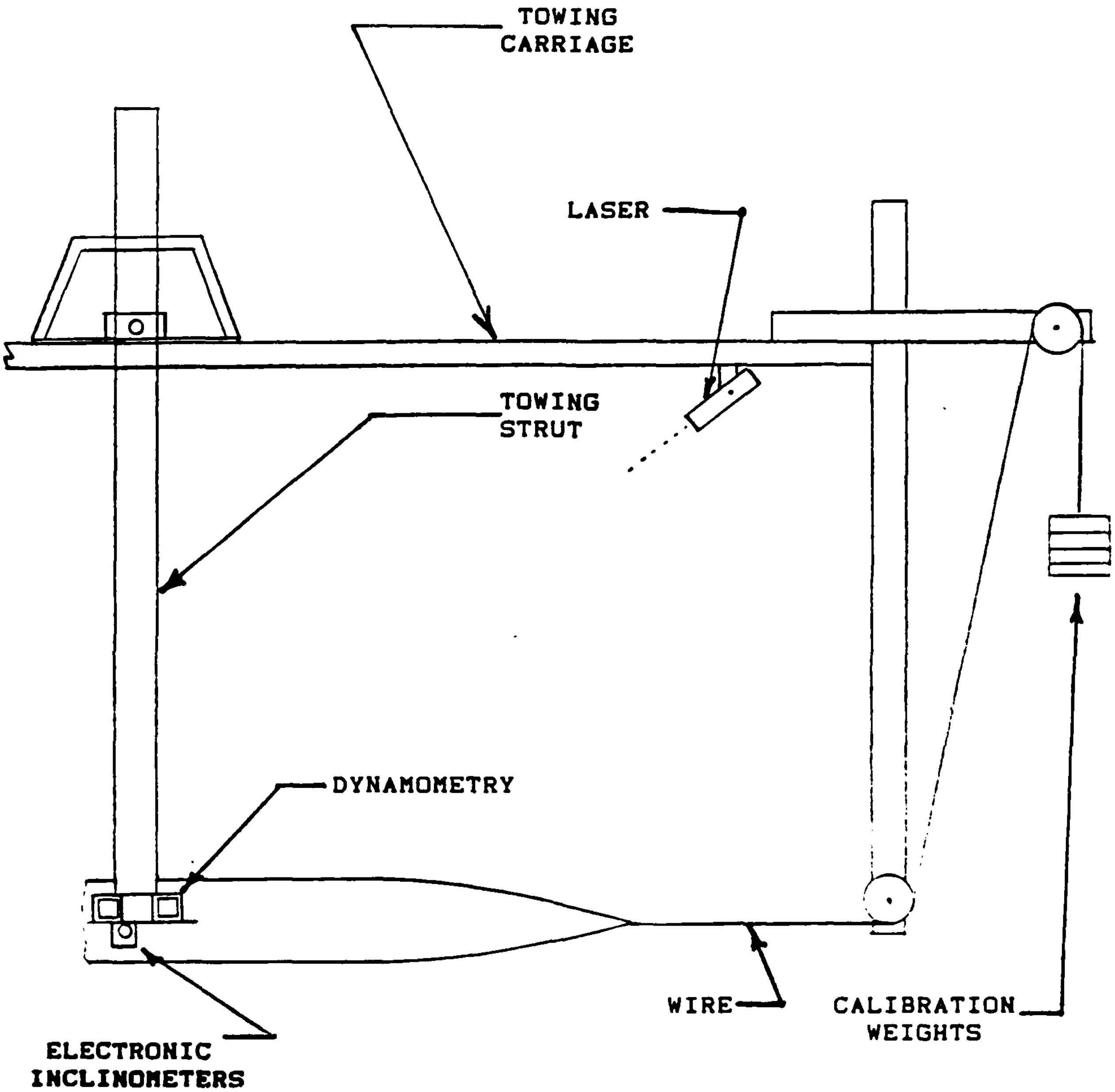
TYPE OF DRIVE SYSTEM AND TOTAL POWER: twin cables attached to high speed carriage, digital control interface with computer, 2 - 150 kw D.C. motors (400% overload capability)

MAXIMUM CARRIAGE SPEED: low speed carriage - 7.6 m/s (25 fps)
high speed carriage - 14 m/s (45 fps)

U.S. NAVAL ACADEMY
HYDROMECHANICS LABORATORY
380 foot TOWING TANK

FIGURE 16

floated out to the strut. Once the strut was bolted to the model, the model was raised from the water and made level with the water surface. The resistance dynamometry was then calibrated in place using a rig specifically built for these tests. Figure 17 is a diagram illustrating the calibration rig. The summed signal from the two force blocks was read for forces in increments of one pound up to twenty pounds. The maximum predicted resistance force was twelve pounds. Once the force calibration was completed, the calibration rig was removed and the submarine was lowered to its running depth of eight feet (one half the depth of the NAHL 380 foot towing tank). The model was then aligned to be parallel to the tank centerline using electronic inclinometers mounted within the model (for trim) and a laser mounted on the towing carriage (for yaw). An initial run at one foot per second was made to check the operation and integrity of the total towing system. For each model, test runs followed at each of nine discrete speeds covering the model speed range. For the models included in this report, a speed range of 1 fps to 9 fps was specified on the basis of the following rationale. Discussions with Mr. William Day of DTNSRDC indicated that the hump in the residual resistance coefficient curve should appear at a Froude number (the ratio of the inertia force to the gravitational force) of about 0.4. This corresponds to a speed of 7.2 fps for a ten foot model. Study of standard references[8,9] on ship model testing indicate that



RESISTANCE CALIBRATION
RIG

FIGURE 17

turbulent flow is reasonable to expect as long as the model Reynolds Number is at least 3.2×10^5. This corresponds to a speed of 0.4 fps for a ten foot model. During the first series of tests, it was determined that there was no wait time required between runs. That is, there was no required waiting period between runs to let wave action die out as is required in surface ship model testing. Once runs covering the speed range were completed, the submarine model was raised and a trip wire was attached at one twentieth of the model's length from the bow. The submarine was then lowered and realigned. Similar tests covering the same range of model speeds were performed on the model appended with the trip wire. Upon completion of the resistance tests, a pattern of tufts was appended to the transition segment of each non-axisymmetric model. The tufts were used to qualitatively observe fluid flow and identify areas of extreme turbulence. Tufts were photographed after the model reached steady speed.

DATA REDUCTION

The total resistance of a deeply submerged submarine (R_T) can be assumed to be separable into two independent parts, the frictional resistance (R_F) and the residuary resistance (R_R) following standard naval architecture practice. On a submerged submarine, the frictional resistance is usually by far the more significant. Because our models were fitted with tail fins and the towing strut protruded from the body, thereby destroying the actual

symmetry of flow over the body, there was an additional resistance force consisting of appendage resistance (R_{APP}) due to the tailfins, and an interference resistance due to the protruding strut (R_{STRUT}). Together, R_{APP} and R_{STRUT} make up a parasitic resistance (R_{PARA}). Therefore, as measured:

$$R_T = R_F + R_R + R_{PARA} \tag{5}$$

In order to expand the resistance data to full scale values, the resistance forces must be non-dimensionalized as described earlier. Converting the resistance forces in equation 5 to resistance coefficients yields the following formula:

$$\frac{R_T}{1/2\,\rho\,SV^2} = \frac{R_F}{1/2\,\rho\,SV^2} + \frac{R_R}{1/2\,\rho\,SV^2} + \frac{R_{PARA}}{1/2\,\rho\,SV^2} \tag{6}$$

Which is equivalent to the following equation:

$$C_T = C_F + C_R + C_{PARA} \tag{7}$$

By rearranging terms, the residuary resistance coefficient can be calculated:

$$C_R = C_T - C_F - C_{PARA} \tag{8}$$

This is the equation used for calculating the residuary resistance coefficient of submarines - the number we seek for the non-axisymmetric forms included in the series.

When testing a submarine model, the only resistance

coefficient that can be calculated directly from the raw model data is the total resistance coefficient (C_T). This means that both the frictional resistance coefficient (C_F), and the parasitic resistance coefficient (C_{para}) must be obtained analytically. As mentioned earlier, the frictional resistance coefficient is relatively easy to obtain. The equation that we used in our data analysis was the ITTC 1957 Model - Ship Correlation Line. See Equation 4.

Calculating the parasitic resistance coefficient is not as easy. There are equations available that will give a value for the resistance coefficient of an air foil[10], or the ITTC 1957 frictional resistance coefficient could be used if the residuary resistance coefficient of the airfoil was considered negligible (i.e. for slender appendages aligned with fluid flow, most of the resistance will be due to friction, not pressure).

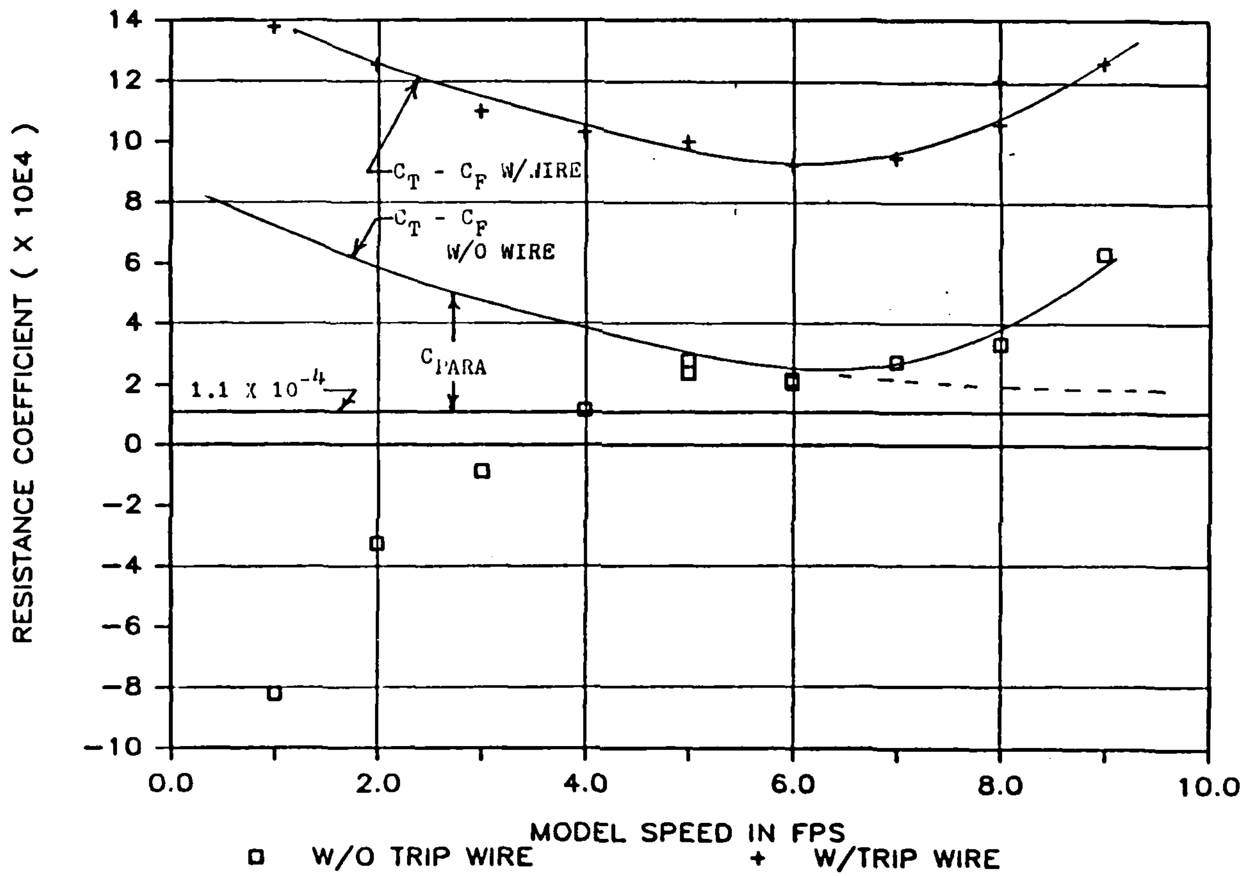
Either of these two approaches is conceptually simple, but their application to a real problem remains difficult because of questions concerning the proper velocity to use for either approach and the hydrodynamic interaction of the appendage with the main body of the submarine. There is, however, no analytical means available to determine the effect of the towing strut on submarine model resistance. We have no concern as to the resistance of the immersed strut since we are measuring resistance at the model end of the strut; but, the interference of the flow off the strut with the portion of the submarine model downstream of the

strut is undefined. Gertler[1], facing similar problems, found the strut interaction coefficient for the double strut towing method to be on the order of 3.5×10^{-4}.

The original method used to calculate the parasitic resistance coefficient was to compare the residuary resistance coefficient of the constant volume axisymmetric submarine model to an accepted standard value. Series 58 is a systematic series of axisymmetric, body of revolution, conventionally shaped submarine models that were tested at DTNSRDC.[1] Subsequently, there were tests done on submarines that had variable length parallel middle bodies with constant nose and tail sections. The model that fit our axisymmetric constant volume submarine had a length to diameter ratio of 10 and incorporated thirty percent of its length as parallel middle body. This submarine model had a residuary resistance coefficient of 1.1×10^{-4}.[11] By making a direct comparison between the standard value and the experimentally determined C_R, values for the parasitic resistance coefficient could be calculated using the following equation:

$$C_{PARA} = C_T - C_F - 1.1\times10^{-4} \qquad (9)$$

This procedure is demonstrated graphically in Figure 18. Because these tests were done before the ITTC formulation for C_F had been adopted, a different standard for the frictional resistance coefficient was used. The equation used in calculating the frictional resistance coefficient in



Parasitic Resistance Calculation

Figure 18

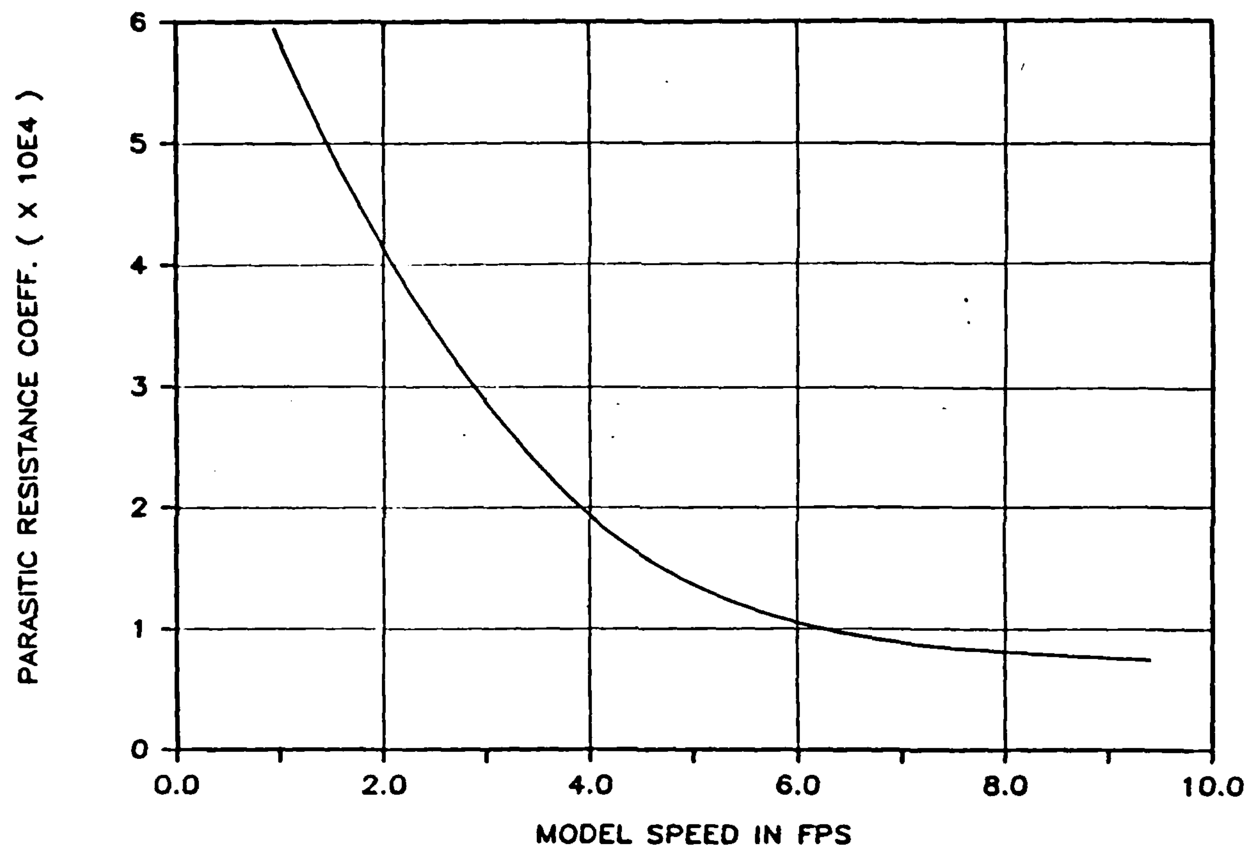
Series 58 was the Schoenherr friction line. Following is the equation for the Schoenherr friction line:

$$\frac{0.242}{\sqrt{C_F}} = \log_{10}(R_N \cdot C_F) \qquad (10)$$

This equation must be solved iteratively. The values obtained for parasitic resistance coefficient were assumed to be functions of model speed alone. This assumption is logical because the appendages were constant on every model tested and it was assumed that the effect of the varying bow shapes on the flow over the afterbody would be negligible. Figure 19 shows the variation of the parasitic resistance coefficient with model speed.

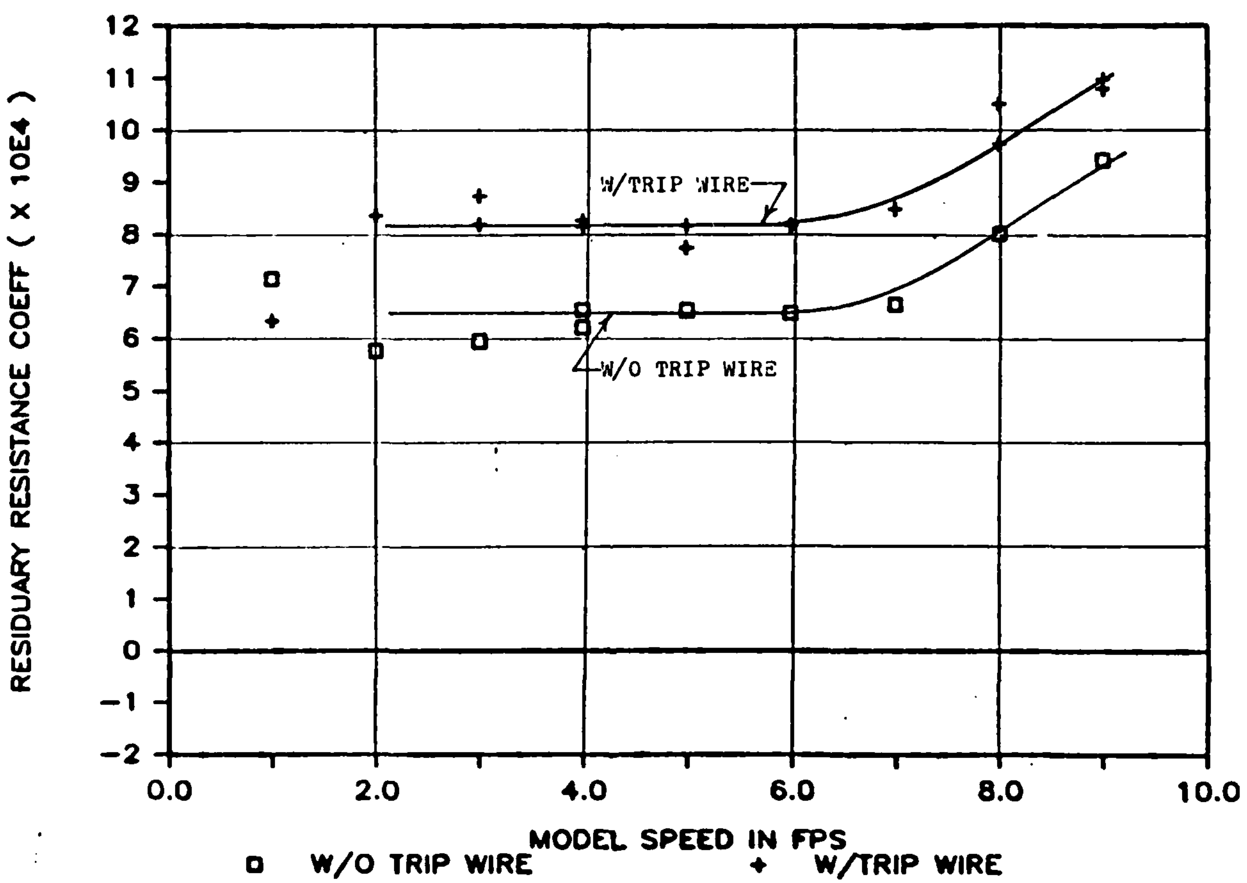
EXPERIMENTAL DATA

Model tests were run on the five submarine models described above. Every effort was made to maintain consistency in experimental technique and data acquisition/analysis among the five tests. The residuary resistance coefficients for the five models were calculated using Equation 8 with the parasitic resistance coefficients calculated from Equation 9. A BASIC computer program that performed this analysis is included in Appendix B. The output of this computer program tabulates the experimental data and the calculated coefficients. These printouts are included in Appendix C. Plots of the residuary resistance coefficient versus model speed for all five models can be found in Figures 20 through 24. A comparison of the five



Parasitic Resistance

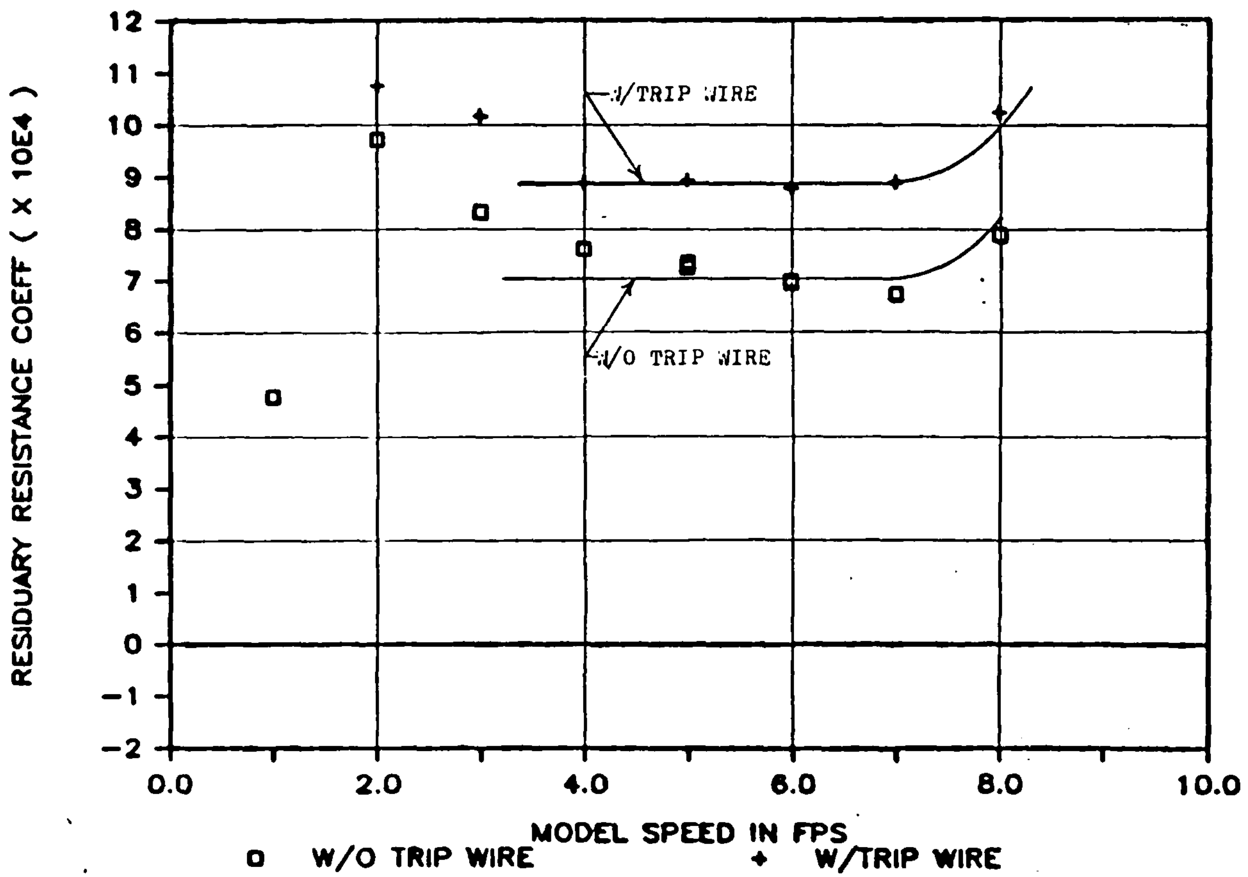
Figure 19



Residuary Resistance Coefficient vs. Model Speed

Long Non-Axisymmetric Bow

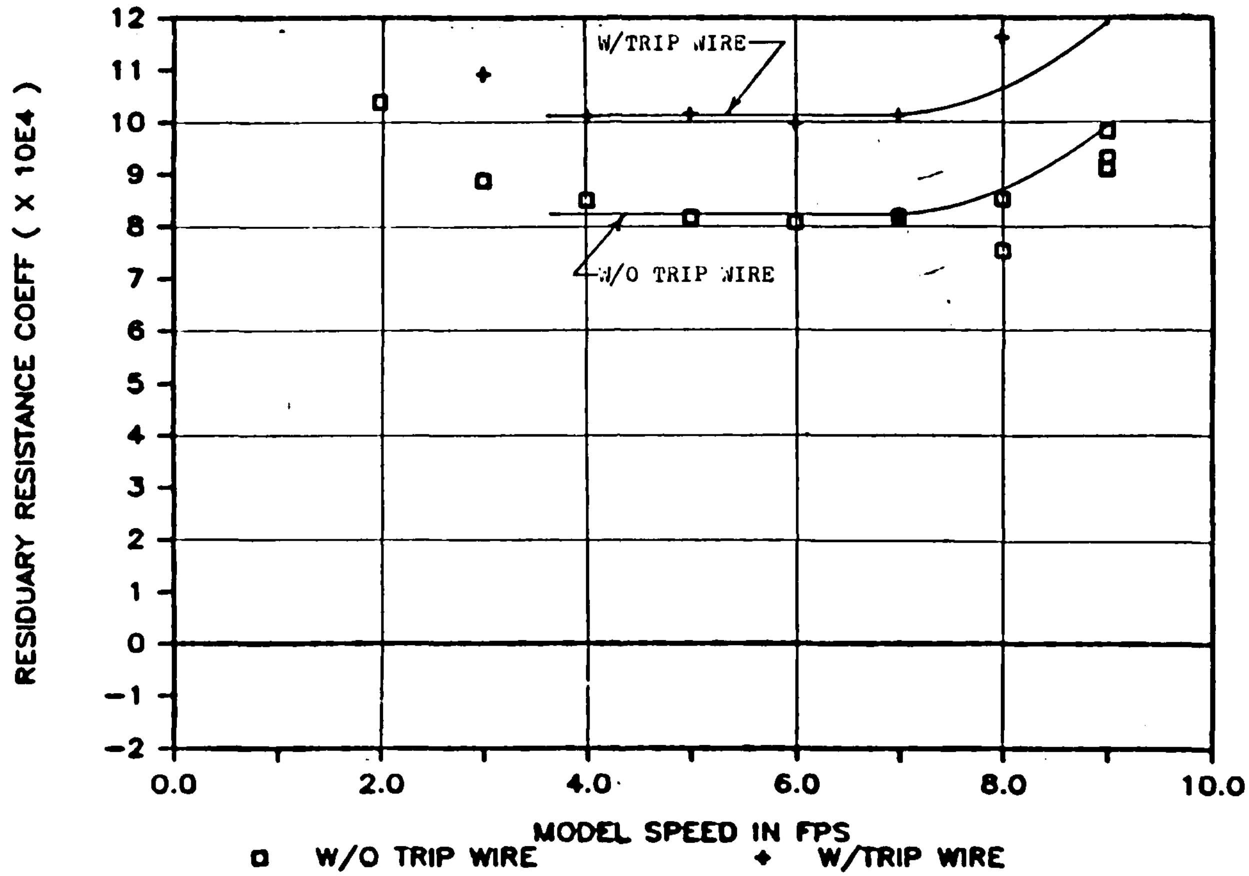
Figure 20



Residuary Resistance Coefficient vs. Model Speed

Medium Non-Axisymmetric Bow

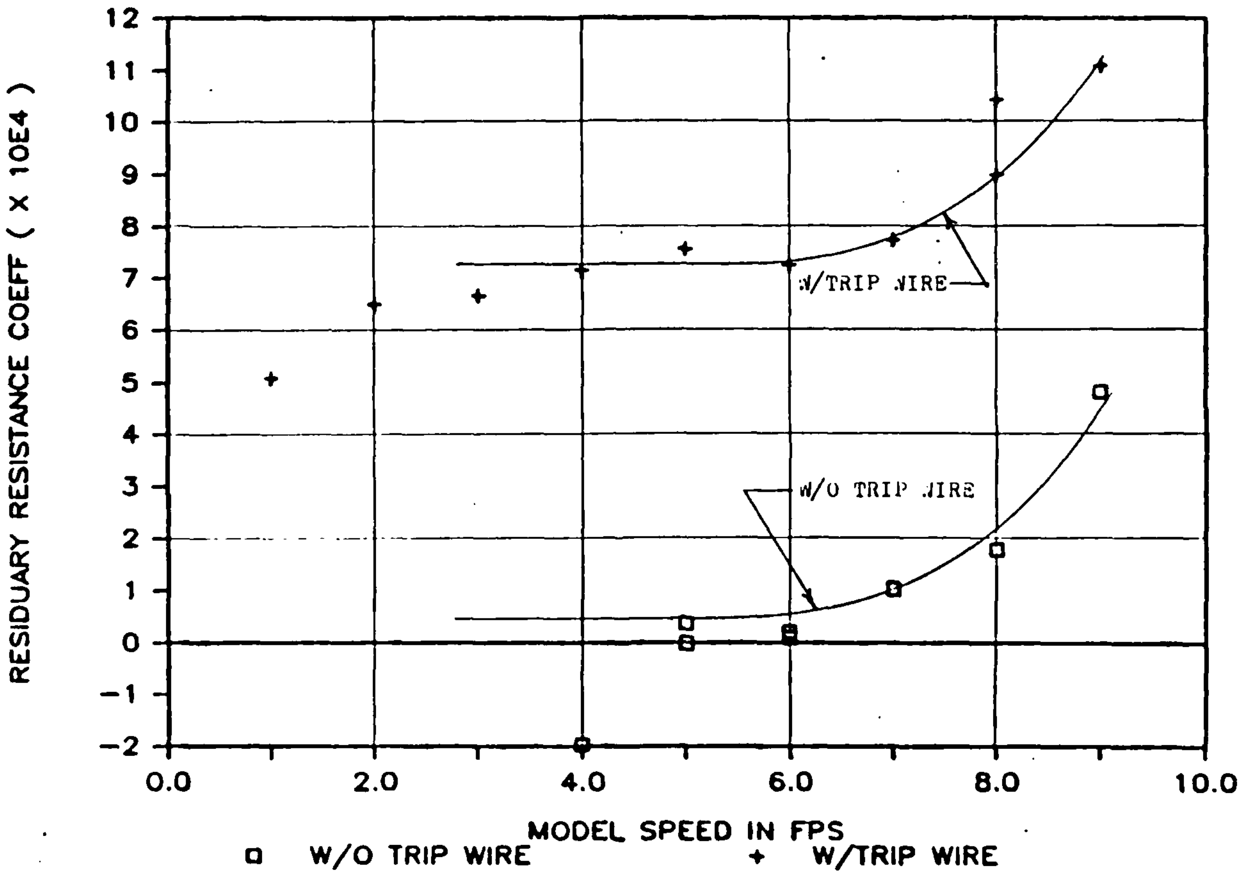
Figure 21



Residuary Resistance Coefficient vs. Model Speed

Short Non-Axisymmetric Bow

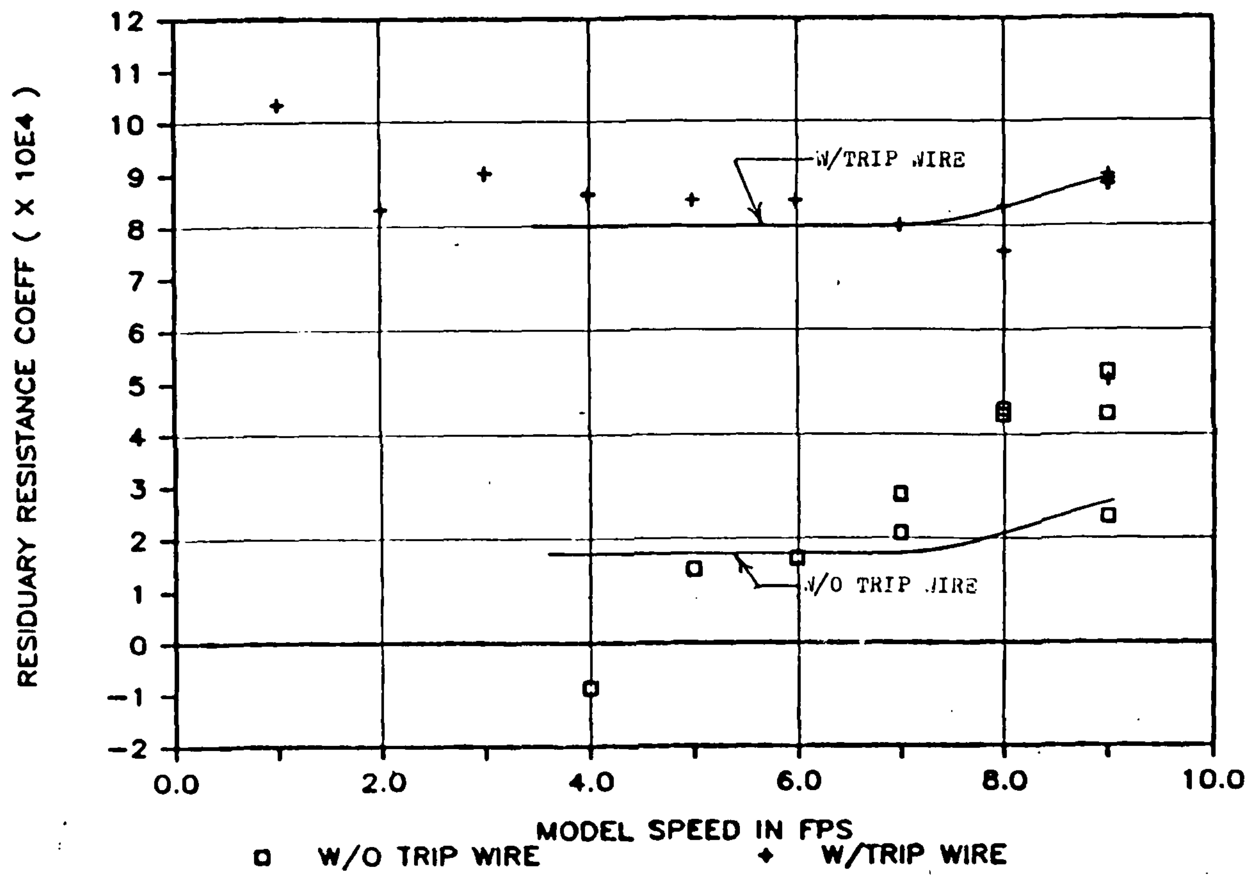
Figure 22



Residuary Resistance Coefficient vs. Model Speed

Constant Volume Axisymmetric Bow

Figure 23



Residuary Resistance Coefficient vs. Model Speed

Constant Length Axisymmetric Bow

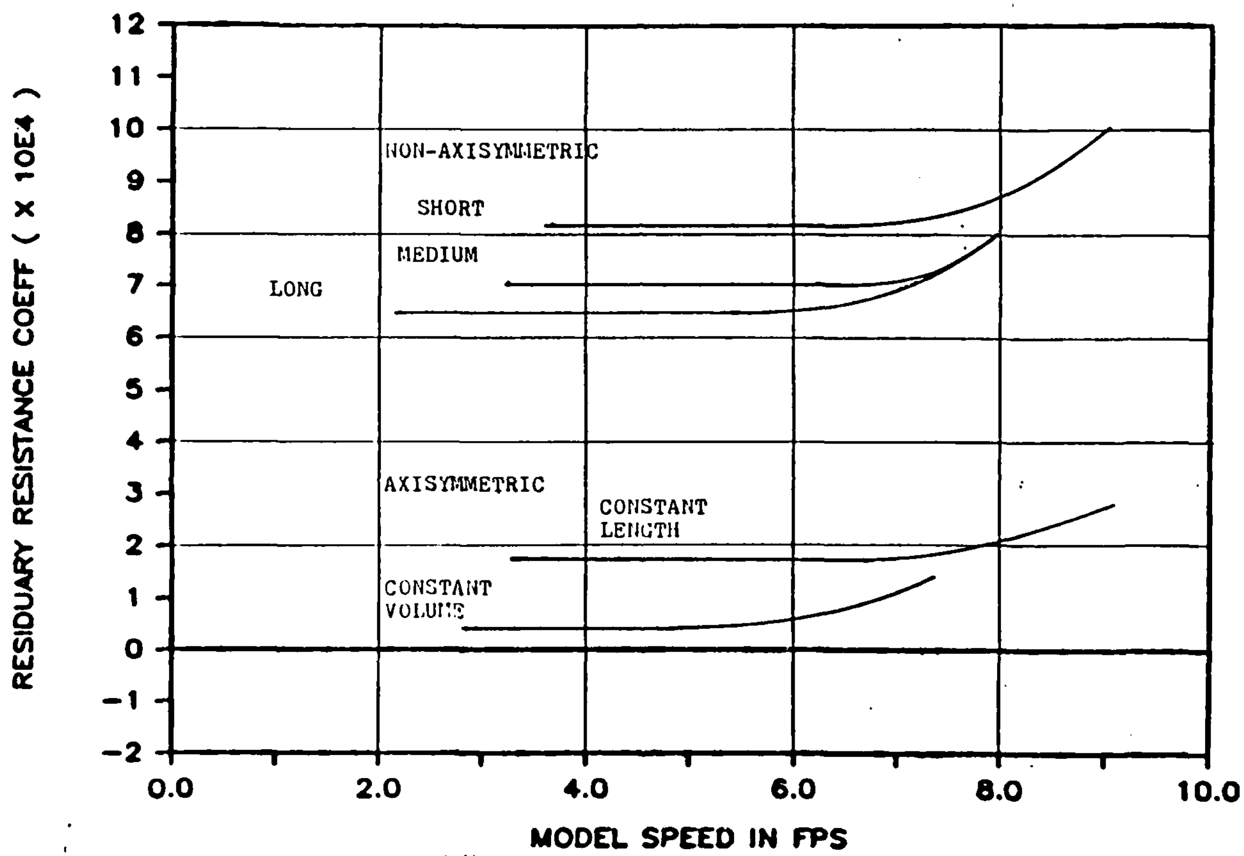
Figure 24

curves can be seen in Figure 25.

DISCUSSION

The experimentally determined residuary resistance coefficient curves for the axisymmetric bows behaved as expected (Figure 11). The residuary resistance coefficient was constant for the stimulated models at the lower speeds and the stimulated and unstimulated curves ran parallel at the higher speeds. The rise in the residuary resistance curve at the higher speeds is called the "wave hump", and it was due to the proximity of the free surface located only eight feet from the model. There is no way to resolve this unwanted phenomenon with fixed geometric constraints.

The residuary resistance coefficient curves for the non-axisymmetric bow shapes tended to rise at the lower speeds. This had not been expected. After consulting with Professor Martin Abkowitz, an expert on submarine resistance and fluid flow, it was determined that this rise was probably due to laminar flow separation. This is a phenomenon that occurs on bodies that have a discontinuity in curvature while they travel in a fluid at low Reynolds numbers. The non-axisymmetric bow forms have a discontinuity in curvature at the forward end of the array. At this point, waterlines change from a constant discrete radius to an infinite radius (i.e. they become straight lines). There is also a sharp change in curvature at the top and bottom of the hull where the array meets the rounded



Residuary Resistance Coefficient vs. Model Speed

Bow Comparison

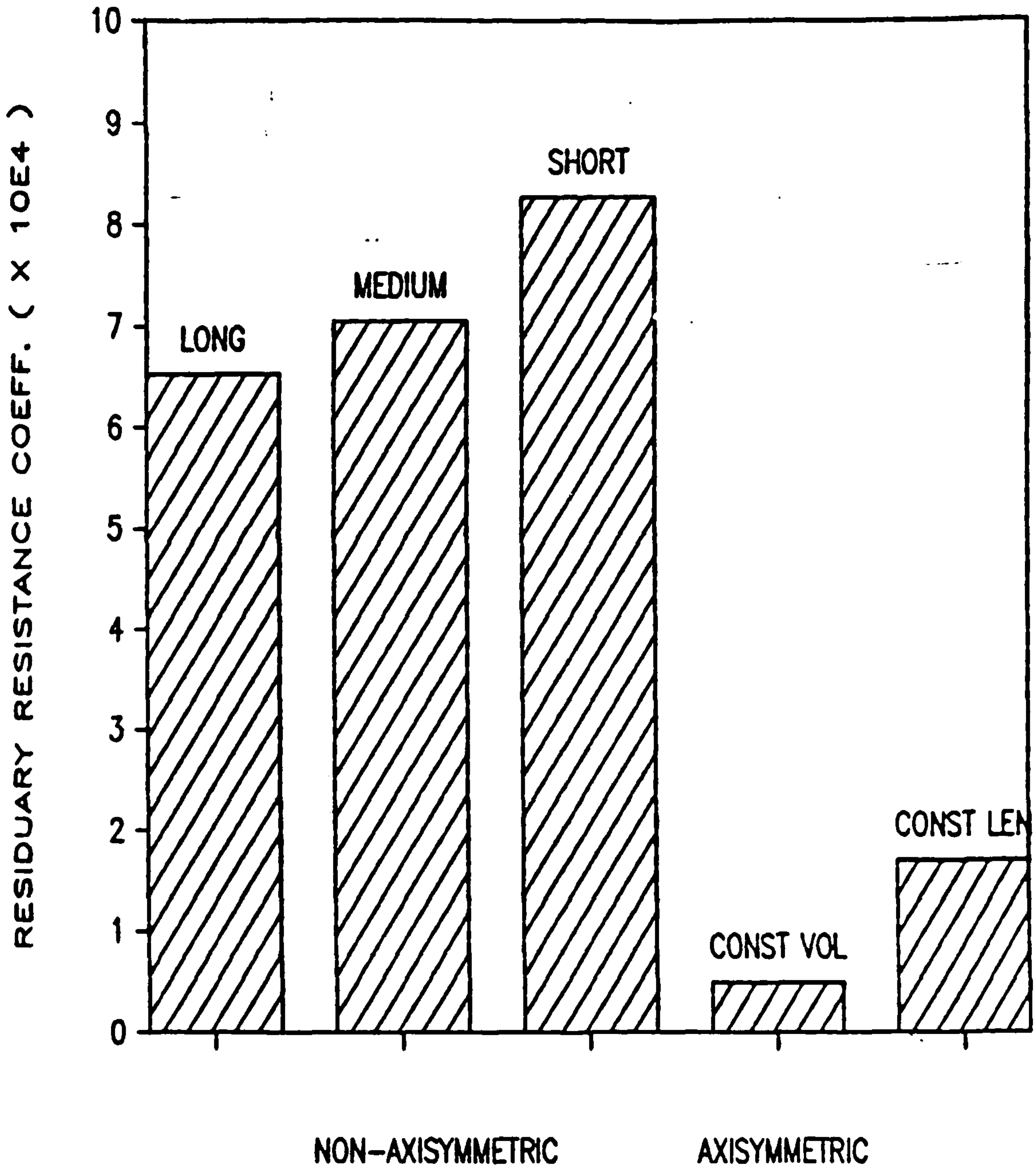
Figure 25

nose.

The laminar flow separation did not disturb our analysis of the data. At higher model speeds (higher Reynolds numbers), where the laminar flow separation was not present, the residuary resistance coefficient was constant with respect to model speed as was predicted. This flat portion of the residuary resistance coefficient curve is where the value for C_R was read. The non-axisymmetric bows also had the wave hump due to the free surface of the tank. The presence of laminar flow separation is a characteristic of these bow shapes that requires further study.

The variation of the residuary resistance coefficient as a function of both bow shape and model speed can be seen in Figure 25. These coefficients are plotted in bar graph form in Figure 26 in order to eliminate the variations with model speed. The large increase in the residuary resistance coefficient for the non-axisymmetric shapes is not as significant as may appear because the frictional resistance, which comprises the greater portion of a submarine's total resistance, must still be taken into account.

An analysis of the photographs taken while the non-axisymmetric models were appended with tufts showed no significant variation among bows. A reversal of flow was observed in the after section of the transition segment for all three non-axisymmetric bows. Separated flow can be reduced or eliminated by reducing unwanted pressure



SUBMARINE COMPARISON

FIGURE 26

gradients. This, in turn, suggests a more gradual transition segment. A series of varying length transition segments would help to clarify the situation.

RESULTS

To assess the practical significance of the hydrodynamic impact of the non-axisymmetric bow shapes studied, a hypothetical prototype submarine size was chosen. Several expansion schemes were available. The principal difference between each scheme was the submarine dimension that remained constant for all five submarines. There were three alternatives considered: keeping the submarine's diameter constant, keeping the submarine's length constant, or keeping the submarine's displaced volume constant. It was arbitrarily chosen to expand all forms to full scale submarines with a maximum diameter of forty feet. Although not a common scaling scheme, it has precedence for submarines since navigational draft constraints on submarine diameter is a real concern. In the expansion, the total resistance coefficient for a bare hull is calculated using the following equation:

$$C_T = C_F + C_R + C_A \qquad (11)$$

In this equation, C_F is calculated using Equation 4, C_R was deduced from the model tests, and C_A is an empirically determined correlation allowance normally included to account for the absence of complete similitude between the

model and the ship. Since we are trying to assess the powering differences for bow shapes and not produce a specific design power estimate, the correlation allowance was taken to be zero.

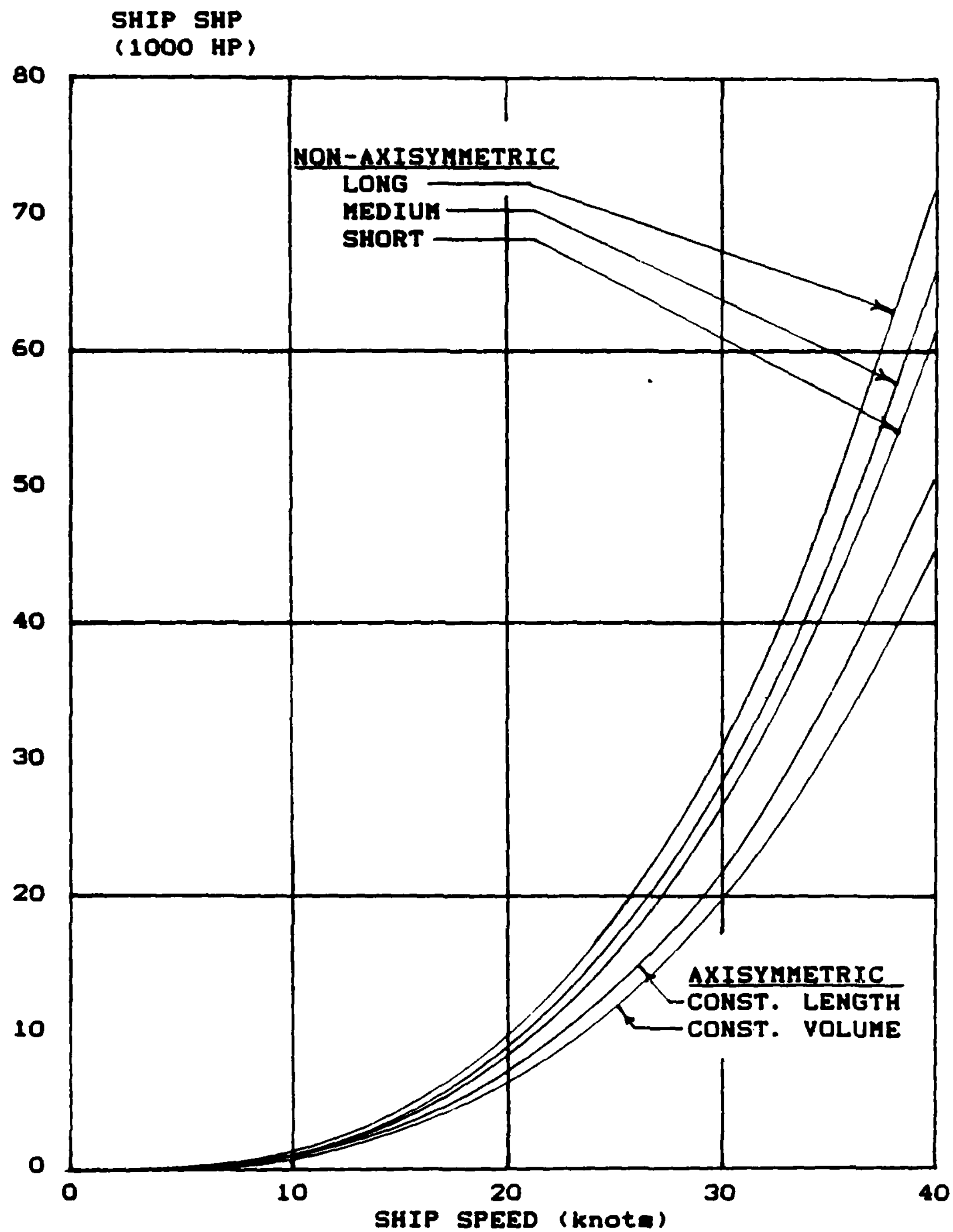
Using the above method, The total resistance coefficient for each prototype submarine was calculated and then converted to the total resistance using Equation 6. With the total resistance, the submarines effective horsepower - the power required to tow the submarine at speed V_s - was calculated. The equation for determining the effective horsepower (EHP) is as follows:

$$EHP = \frac{R_T \cdot V_s}{550} \tag{12}$$

The shaft horsepower , the power required from the propulsion plant, can be calculated as follows:

$$SHP = \frac{EHP}{PC} \tag{13}$$

In this equation, PC is the propulsive coefficient, a measure of the submarine's propulsive efficiency. Figure 27 illustrates the variation of SHP with ship speed for each submarine tested assuming a PC of 0.75. By comparing the speed - power curve for the medium length non-axisymmetric bow submarine with those of the equal length and equal volume axisymmetric bow submarines provides insight into the powering difference for constant L/D and displacement, respectively. Relative to the medium length non-



Note: All submarines have a 40 foot maximum diameter and a PC of 0.75.

SHP COMPARISON

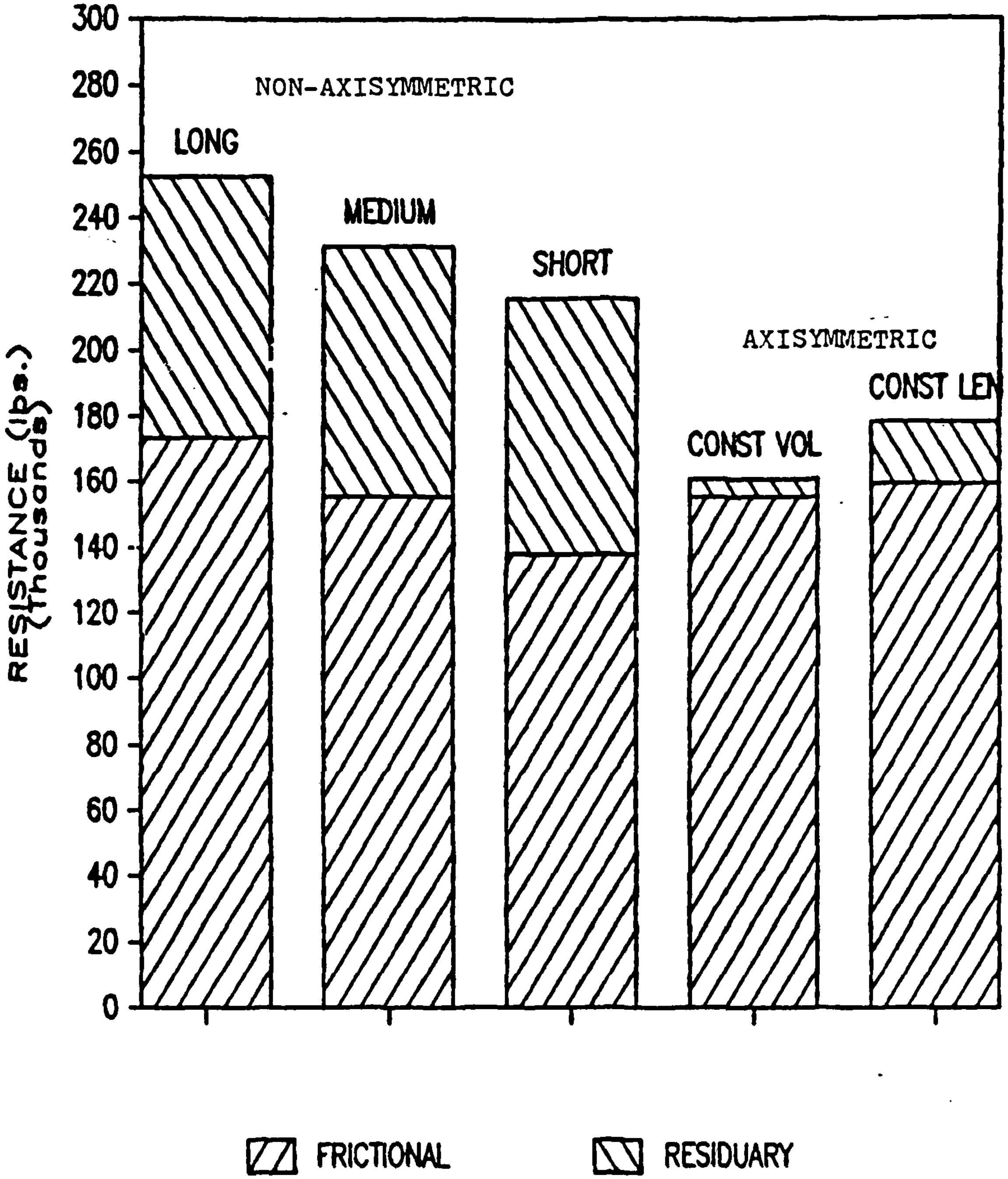
FIGURE 27

axisymmetric bow submarine, the long bow submarine has a 12.7% greater length with 11.5% more displacement. Similarly, the short non-axisymmetric bow submarine has a 12.0% shorter hull with 10.0% less displacement. Figure 28 presents a resistance breakdown for each submarine tested at a ship's speed of thirty knots. Even though the residuary resistance coefficient for the short bow non-axisymmetric model had the greatest value, it can be seen that the larger frictional resistance of the other two non-axisymmetric models was dominant (due to the increase in wetted surface). Figure 29 is a bar chart that demonstrates the deeply submerged maximum speed that the submarine could attain if it had an installed SHP of 45,000 horse power and a PC of 0.75 (EHP = 33,750). This plot actually demonstrates the "price" of the proposed sonar system - the speed loss that the submarine would have to accept to acquire improved sonar performance.

CONCLUSIONS

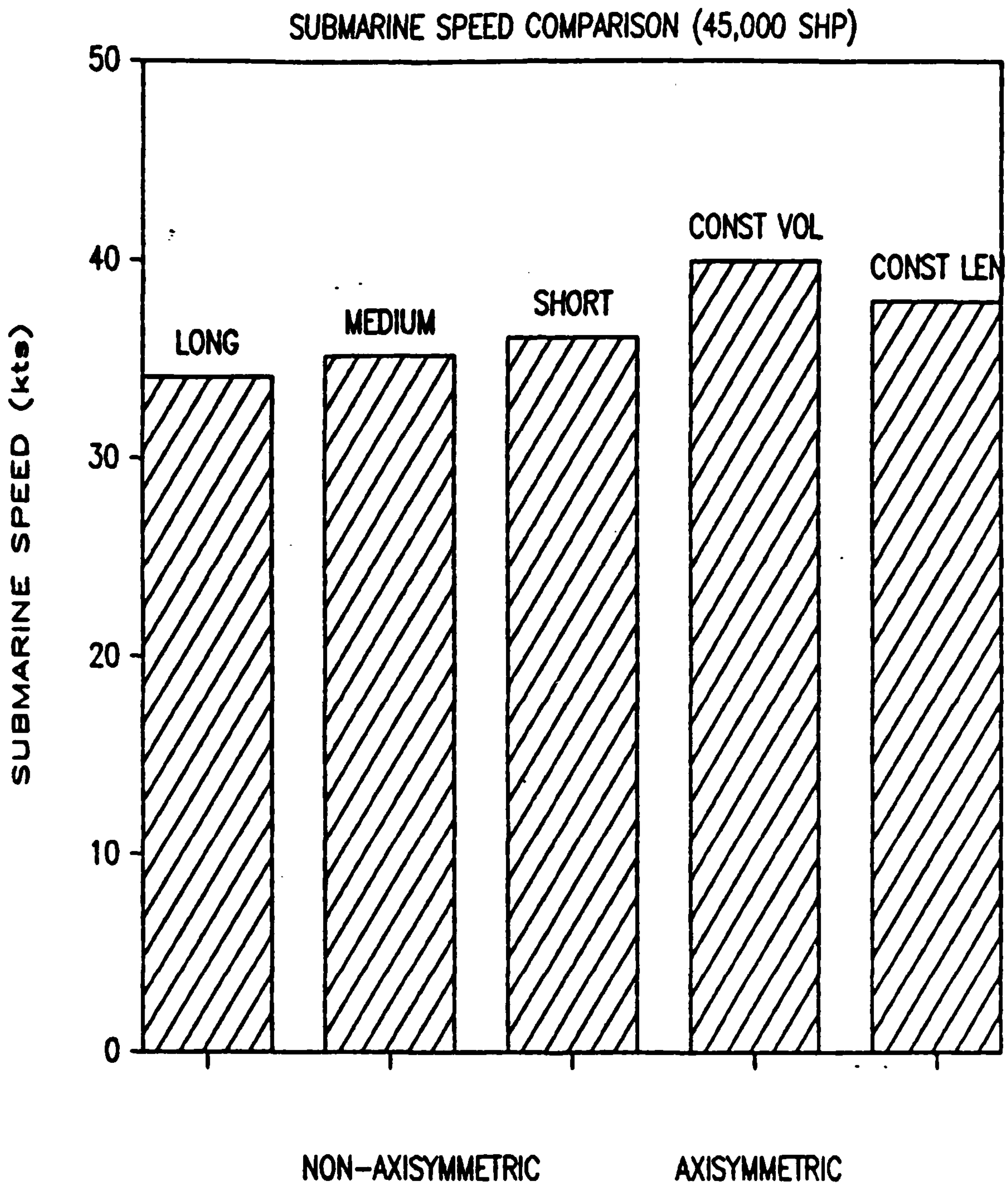
In this study, the author set out to determine the hydrodynamic impact of a new bow form that could possibly be used for future U.S. Navy submarines. This bow form was designed to house a vertically oriented cylindrical array sonar system. A large cylindrical sonar array located in the bow of a submarine has potential benefits over the sonar systems presently being used.

The hydrodynamic impact has been presented as a speed



Thirty Knot Resistance Comparison

Figure 28



SPEED COMPARISON
FIGURE 29

loss for equally powered axisymmetric and non-axisymmetric submarines. The series of submarines was expanded to prototypes with a maximum diameter (beam) of forty feet. The prototype long, medium, and short bow non-axisymmetric submarines experienced fifteen, twelve, and ten percent speed losses respectively when compared to the constant volume axisymmetric submarine. While the short non-axisymmetric submarine had the smallest speed loss of the three non-axisymmetric bows tested, it also had the shortest array length and displaced volume. Although the longest non-axisymmetric submarine had the greatest powering requirements, it must be noted that this prototype had the longest array length and the greatest displaced volume (allowing it to carry the largest payload).

There was no intent in this study to pick an "optimum" array length. A comprehensive study contrasting the advantages of each bow configuration with its corresponding hydrodynamic performance would be required before such a decision could be effectively made. The results of this experiment will allow the preliminary designers of U.S. Navy submarines to perform such a study.

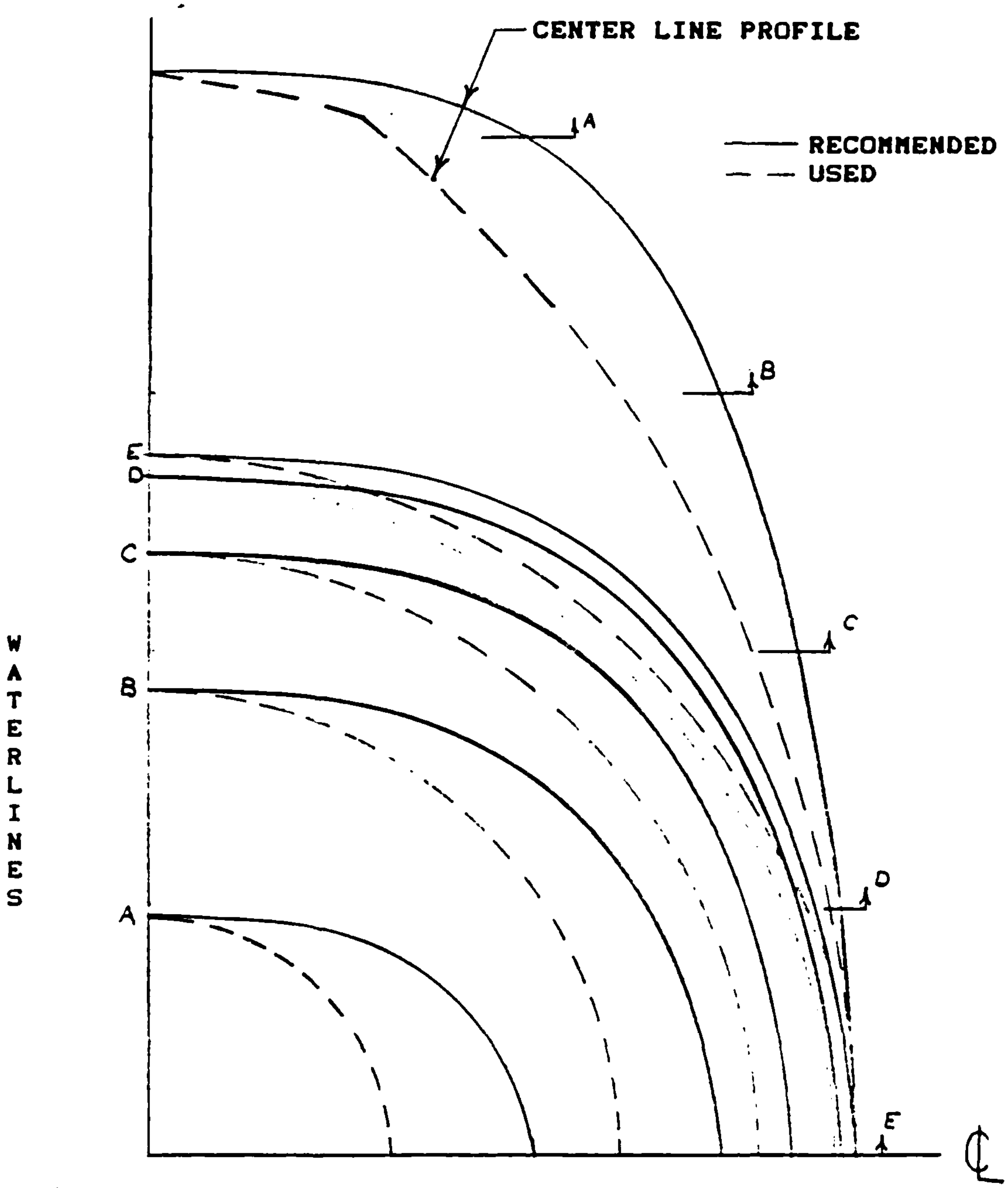
RECOMMENDATIONS FOR FUTURE STUDY

The discontinuity of curvature in the bow shape is one topic for which future study is recommended. New waterplane shapes have been developed that avoid the discontinuity. These waterplane shapes followed the same equations from

which the axisymmetric bow shapes were formed. Figure 30 compares the recommended shape to the shape used in the model tests. Included in Appendix D are a table of offsets for the new shape and a computer program that computed these offsets.

Other areas of interest that should be studied include an investigation into the pressure fluctuations about the bow and transition segment. This study could be accomplished by installing pressure taps into one or all of the bows tested in this program.

A series that used the length of the transition segment as an independent variable could be used to analyze flow in the transition region. Such a series could be used in determining the minimum transition length that would eliminate unwanted flow effects.



NEW WATERLINE SHAPES

FIGURE 30

ACKNOWLEDGMENTS

The author of this Trident Scholar Report wishes to gratefully acknowledge the assistance of the following people:

Capt. Harry Jackson, USN (ret.) for providing the starting point for the project.

Mr. Tom Price of the U. S. Naval Academy Technical Support Department for the production of the submarine bows tested during the project.

Mr. John Hill and the entire staff of the Naval Academy Hydromechanics Laboratory for their aid in conducting the model tests.

And most importantly, Dr. Roger Compton of the Naval Academy faculty and Mr. Howard Chatterton presently of Coast Guard Headquarters who served as Trident Scholar advisors.

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APPENDIX A:

GLOSSARY

<u>Appendage resistance</u>: (R_{APP}) The component of the total resistance that is due to the drag of appendages on the ship or model.

<u>Axisymmetric</u>: Symmetric about a longitudinal axis.

<u>Blockage</u>: The effect of the boundaries of a channel or tunnel on the flow around a body.[12]

<u>Body of revolution</u>: A body that is symmetric about a longitudinal axis; all cross sections are circles.

<u>Dynamic similitude</u>: The ratio of all forces to the inertia force are the same for model and ship.

<u>Dynamometry</u>: The resistance measuring apparatus.

<u>Effective horse power</u>: (EHP) the power required to tow a ship.

<u>Frictional resistance</u>: (R_F) The component of resistance obtained by integrating the tangential stresses over the surface of a body in the direction of motion. [12]

<u>Froude number</u>: The ratio of the inertia force to the gravitational force. The Froude number can be calculated using the formula: $F_N = V/\sqrt{Lg}$.

<u>Geometric similitude</u>: The model is a perfecty scaled replica of the ship.

<u>Kinematic similitude</u>: The ratios between fluid velocities around the model must be equal to the ratios of the corresponding velocities around the ship.[8]

<u>Laminar Flow</u>: The fluid moves in laminas or layers.[8]

<u>Munk moment</u>: The yawing moment on a submerged body having forward speed.

<u>Parallel middle body</u>: The amidship portion of a ship within which the contour of the hull form is unchanged.[12]

<u>Parasitic resistance</u>: (R_{PARA}) The component of the total resistance of the model that remains after the frictional and residuary resistance forces are accounted for.

<u>Pitch</u>: The angular component of the motion of a hull about a transverse axis. [12]

<u>Pressure resistance</u>: (pressure drag, R_{PR}) The component of resistance obtained by integrating the normal stresses over the surface of a body in the direction of motion. [12]

<u>Prismatic coefficient</u>: (C_P) The ratio of the volume of displacement to the volume of a cylinder having the length and cross section of the maximum section of the ship. [12]

<u>Propulsive coefficient</u>: (PC) The ratio of the effective horsepower to the shaft horsepower. An efficiency rating of the propulsion system.

<u>Residuary resistance</u>: (R_R) A quantity obtained by subtracting from the total resistance of a hull a calculated frictional resistance. [12]

<u>Reynolds number</u>: The ratio of the inertia forces to the viscous forces. The Reynolds number can be calculated using the following equation: $R_N = V \cdot L/\nu$.

<u>Shaft horsepower</u>: (SHP) The required power at the propeller shaft to propel the ship.

<u>Strut interference resistance</u>: (R_{STRUT}) The component of the total resistance created by the disturbed flow in the wake of the submarine model towing strut.

<u>Total resistance</u>: (R_T) The fluid force acting on a body in such a way as to oppose its motion. [12]

<u>Tufts</u>: Small pieces of yarn connected to a model to qualitatively examine fluid flow.

<u>Turbulent flow</u>: Flow in which the fluids velocity components have random fluctuations. [8]

<u>Wetted surface</u>: (S) The surface area of a hull form below the water line. The total surface of the hull for a submerged submarine.

<u>Yaw</u>: The angular component of the motion of a hull about a vertical axis. [12]

APPENDIX B:

COMPUTER PROGRAMS

TRANSITION OFFSETS

```
100 REM ***************************************************************
110 REM **                                                           **
120 REM **    John V. De Nuto                       8/07/85          **
130 REM **    Trident Scholar Project               USNA             **
140 REM **                                                           **
150 REM **      This program will calculate the offsets              **
160 REM **  for the transition region for the submarine              **
170 REM **  being studied in the above project.                       **
180 REM **                                                           **
190 REM ***************************************************************
200 INPUT "Length of array (full scale)=",L
210 FOR H = 0 TO 20 STEP 5
220    LET YE = SQR(625 - H^2) - 10
230    LET YE2 = SQR(156.25 - (H - 7.5)^2)
240    LET YC = SQR(400 - H^2)
250    LET DY1 = 2/L
260    IF H > 15 GOTO 270 ELSE GOTO 300
270         LET YE = YE2
280         LET DY1 = 0
300    LET Y2 = YC - YE
310    LET A = (Y2 - 17.5*DY1)/(-21437.75)
320    LET H1 = 17.5 + DY1/(210*A)
330    LET B = DY1 - 3*A*H1^2
340    LET C = A*H1^3 + B*H1
350    PRINT
360    PRINT "WL=";H
370    PRINT "A","B","C","h"
380    PRINT A,B,C,H1
390    PRINT
400    PRINT "X","Y"
410    FOR X = 0 TO 35 STEP 5
420     LET Y = A*(X-H1)^3 + B*(X-H1) + C
430     PRINT X, Y + YE
440     NEXT X
450    NEXT H
460 END
```

SUBMARINE RESISTANCE ANALYSIS

```
100 ' SUBMARINE RESISTANCE ANALYSIS
110 ' INPUT: L, WS, DENSITY, VISCOSITY, NUMBER RUNS, SPEED
(fps), RESISTANCE (lbs.)
120 ' CALCULATES CR USING VALUES FOR CA CALCULATED FROM THE
AXISYMMETRIC SUB
130 ' OUTPUT: RN, FN, CT, CF(ITTC), CR
140 R$ = SPACE$(25)
150 T$ = STRING$(40,42)
160 CLS : PRINT R$;T$
170 PRINT R$;"*";SPC(38);"*"
180 PRINT R$;"*";SPC(9);"SUBMARINE RESISTANCE";SPC(9);"*"
190 PRINT R$;"*";SPC(16);"PROGRAM";SPC(15);"*"
200 PRINT R$;"*";SPC(38);"*"
210 PRINT R$;"*";SPC(18);"by";SPC(18);"*"
220 PRINT R$;"*";SPC(38);"*"
230 PRINT R$;"*";SPC(12);"J. V. DE NUTO";SPC(13);"*"
240 PRINT R$;"*";SPC(13);"MARCH, 1986";SPC(14);"*"
250 PRINT R$;"*";SPC(38);"*"
260 PRINT R$;T$ : PRINT
270 PRINT R$; : INPUT "NAME OF INPUT DATA FILE:";DAT$
280 G$ = "          ##.### ##.###  ##.###^^^^  ##.###^^^^
##.###^^^^ ##.##^^^^  ##.###^^^^"
290 OPEN "I", #1, "B:" + DAT$
300 INPUT #1, TITLE$
310 PRINT : PRINT R$;TITLE$ : PRINT
320 INPUT #1, L, WS, LA, WSA, DEN, KV, N
330 PRINT R$;"MODEL LENGTH = ";L;" ft."
340 PRINT R$;"WETTED SURFACE = ";WS;" ft^2"
350 PRINT R$;"APPENDAGE LENGTH = ";LA;" ft."
360 PRINT R$;"APPENDAGE WETTED SURFACE = ";WSA;" ft^2"
370 PRINT R$;"DENSITY = ";DEN;" lb-s^2 / ft^4"
380 PRINT R$;"KINEMATIC VISCOSITY = "; :PRINT USING
"##.####^^^^";KV;
390 PRINT " ft^2 / s" : PRINT : PRINT
400 FOR I = 1 TO 2000 : NEXT I
410 CLS
420 PRINT "          SPEED  RESISTANCE  Rn      Ct
Cf (ITTC)    Ca        Cr"
430 PRINT "          (fps)   (lbs)" : PRINT
440 FOR I=1 TO N
450     INPUT #1, V, R
460     CT = R/(.5*DEN*WS*V^2)
470     RN = V*L/KV
490     CF = .075/(LOG(RN)/LOG(10) - 2)^2
500     IF V>.5 AND V<.8 THEN CA = .00067
510     IF V>.9 AND V<1.1 THEN CA = .000587
520     IF V>1.9 AND V<2.1 THEN CA = .00042
530     IF V>2.9 AND V<3.1 THEN CA = .00029
540     IF V>3.9 AND V<4.1 THEN CA = .000195
550     IF V>4.4 AND V<4.6 THEN CA = .000162
560     IF V>4.9 AND V<5.1 THEN CA = .000138
```

```
570     IF V>5.4 AND V<5.6 THEN CA = .000119
580     IF V>5.9 AND V<6.1 THEN CA = .000105
590     IF V>6.4 AND V<6.6 THEN CA = 9.600001E-05
600     IF V>6.9 AND V<7.1 THEN CA = .00009
610     IF V>7.4 AND V<7.6 THEN CA = 8.550001E-05
620     IF V>7.9 AND V<8.100001 THEN CA = .000082
630     IF V>8.399999 AND V<8.600001 THEN CA = .00008
640     IF V>8.899999 AND V<9.100001 THEN CA = .00008
650     CR = CT - CF - CA
660     PRINT USING G$; V, R, RN, CT, CF, CA, CR
670 NEXT I
680 END
```

SUBMARINE EHP ANALYSIS

```
100 ' SUBMARINE POWERING ANALYSIS
110 ' INPUT: L, WS, C(r), SCALE RATIO, PC
130 ' OUTPUT: SHIP RESISTANCE, EHP, SHP
140 R$ = SPACE$(25)
150 T$ = STRING$(40,42)
160 CLS : PRINT R$;T$
170 PRINT R$;"*";SPC(38);"*"
180 PRINT R$;"*";SPC(10);"SUBMARINE POWERING";SPC(10);"*"
190 PRINT R$;"*";SPC(16);"PROGRAM";SPC(15);"*"
200 PRINT R$;"*";SPC(38);"*"
210 PRINT R$;"*";SPC(18);"by";SPC(18);"*"
220 PRINT R$;"*";SPC(38);"*"
230 PRINT R$;"*";SPC(12);"J. V. DE NUTO";SPC(13);"*"
240 PRINT R$;"*";SPC(14);"APRIL 1986";SPC(14);"*"
250 PRINT R$;"*";SPC(38);"*"
260 PRINT R$;T$ : PRINT
400 FOR I = 1 TO 2000 : NEXT I
410 CLS
510 PRINT
520 INPUT "     MODEL NAME :";A$
530 INPUT "     MODEL LENGTH (ft) :";L
540 INPUT "     MODEL WETTED SURFACE :";S
545 INPUT "     RESIDUARY RESISTANCE COEFFICIENT :";CR
550 INPUT "     SCALE RATIO :";T
560 INPUT "     PROPULSIVE COEFFICIENT :";PC
570 PRINT : PRINT : PRINT
580   PRINT   "     SPEED      R(f)        R(r)         R(t)
EHP        SHP"
590   PRINT   "     (kts)      (lbs)       (lbs)        (lbs)
(HP)       (HP)"
600 PRINT
601 LS = L * T : SS = S * T^2
602  G$  =   "     ###.#    #######.#    #######.#    #######.#
######.#   ######.#"
610 FOR VK = 5 TO 40 STEP 5
620 V = VK * 1.689
625 RN = V * LS / 1.2791E-05
630 CF = .075/(LOG(RN)/LOG(10) - 2)^2
640 RF = CF * .9953 * SS * V^2
650 RR = CR * .9953 * SS * V^2
660 RT = RF + RR
670 EHP = RT * V / 550
680 SHP = EHP / PC
690 PRINT USING G$; VK,RF,RR,RT,EHP,SHP
700 NEXT VK
```

APPENDIX C:

MODEL TEST DATA

```
*************************************
*                                   *
*       SUBMARINE RESISTANCE        *
*             PROGRAM               *
*                                   *
*               by                  *
*                                   *
*          J. V. DE NUTO            *
*           MARCH, 1986             *
*                                   *
*************************************
```

NAME OF INPUT DATA FILE:? SUBDAT1

LONG BOW W/O TRIP WIRE 10/17/85

MODEL LENGTH = 12 ft.
WETTED SURFACE = 33.569 ft^2
APPENDAGE LENGTH = .5 ft.
APPENDAGE WETTED SURFACE = 1.849 ft^2
DENSITY = 1.9367 lb-s^2 / ft^4
KINEMATIC VISCOSITY = 1.0804E-05 ft^2 / s

SPEED (fps)	RESISTANCE (lbs)	Rn	Ct	Cf (ITTC)	Cpara	Cr
3.991	2.239	4.433E+06	4.323E-03	3.474E-03	1.95E-04	6.546E-04
4.989	3.338	5.542E+06	4.125E-03	3.333E-03	1.38E-04	6.539E-04
5.987	4.636	6.650E+06	3.979E-03	3.224E-03	1.05E-04	6.491E-04
6.986	6.174	7.759E+06	3.892E-03	3.137E-03	9.00E-05	6.656E-04
7.983	8.177	8.867E+06	3.947E-03	3.064E-03	8.20E-05	8.015E-04
7.984	8.178	8.867E+06	3.947E-03	3.064E-03	8.20E-05	8.014E-04
8.981	10.554	9.975E+06	4.025E-03	3.001E-03	8.00E-05	9.440E-04

```
****************************************
*                                      *
*         SUBMARINE RESISTANCE         *
*               PROGRAM                *
*                                      *
*                 by                   *
*                                      *
*           J. V. DE NUTO              *
*            MARCH, 1986               *
*                                      *
****************************************
```

NAME OF INPUT DATA FILE:? SUBDAT2

LONG BOW W/TRIP WIRE   10/17/85

MODEL LENGTH = 12 ft.
WETTED SURFACE = 33.569 ft^2
APPENDAGE LENGTH = .5 ft.
APPENDAGE WETTED SURFACE = 1.849 ft^2
DENSITY = 1.9367 lb-s^2 / ft^4
KINEMATIC VISCOSITY = 1.0804E-05 ft^2 / s

SPEED (fps)	RESISTANCE (lbs)	Rn	Ct	Cf (ITTC)	Cpara	Cr
0.998	0.217	1.108E+06	6.702E-03	4.585E-03	5.87E-04	1.530E-03
1.996	0.677	2.217E+06	5.227E-03	3.971E-03	4.20E-04	8.359E-04
2.994	1.392	3.325E+06	4.777E-03	3.668E-03	2.90E-04	8.194E-04
3.992	2.323	4.434E+06	4.484E-03	3.473E-03	1.95E-04	8.152E-04
4.990	3.436	5.542E+06	4.246E-03	3.333E-03	1.38E-04	7.747E-04
5.988	4.833	6.650E+06	4.147E-03	3.224E-03	1.05E-04	8.175E-04
6.986	6.466	7.759E+06	4.076E-03	3.137E-03	9.00E-05	8.489E-04
7.983	8.694	8.867E+06	4.196E-03	3.064E-03	8.20E-05	1.051E-03
8.983	10.964	9.977E+06	4.180E-03	3.001E-03	8.00E-05	1.099E-03
8.981	10.911	9.975E+06	4.162E-03	3.001E-03	8.00E-05	1.080E-03

```
****************************************
*                                      *
*        SUBMARINE RESISTANCE          *
*              PROGRAM                 *
*                                      *
*                 by                   *
*                                      *
*           J. V. DE NUTO              *
*           MARCH, 1986                *
*                                      *
****************************************
```

NAME OF INPUT DATA FILE:? SUBDAT3

LONG BOW W/O TRIP WIRE 10/18/85

MODEL LENGTH = 12 ft.
WETTED SURFACE = 33.569 ft^2
APPENDAGE LENGTH = .5 ft.
APPENDAGE WETTED SURFACE = 1.849 ft^2
DENSITY = 1.9367 lb-s^2 / ft^4
KINEMATIC VISCOSITY = 1.0804E-05 ft^2 / s

SPEED (fps)	RESISTANCE (lbs)	Rn	Ct	Cf (ITTC)	Cpara	Cr
0.698	0.097	7.757E+05	6.145E-03	4.957E-03	6.70E-04	5.178E-04
0.998	0.190	1.108E+06	5.887E-03	4.585E-03	5.87E-04	7.148E-04
1.996	0.643	2.217E+06	4.969E-03	3.971E-03	4.20E-04	5.773E-04
2.993	1.326	3.324E+06	4.554E-03	3.668E-03	2.90E-04	5.955E-04
3.992	2.222	4.434E+06	4.289E-03	3.473E-03	1.95E-04	6.208E-04

```
****************************************
*                                      *
*        SUBMARINE RESISTANCE          *
*              PROGRAM                 *
*                                      *
*                 by                   *
*                                      *
*          J. V. DE NUTO               *
*           MARCH, 1986                *
*                                      *
****************************************
```

NAME OF INPUT DATA FILE:? SUBDAT4

LONG BOW W/TRIP WIRE 10/18/85

MODEL LENGTH = 12 ft.
WETTED SURFACE = 33.569 ft^2
APPENDAGE LENGTH = .5 ft.
APPENDAGE WETTED SURFACE = 1.849 ft^2
DENSITY = 1.9367 lb-s^2 / ft^4
KINEMATIC VISCOSITY = 1.0804E-05 ft^2 / s

SPEED (fps)	RESISTANCE (lbs)	Rn	Ct	Cf (ITTC)	Cpara	Cr
0.998	0.188	1.108E+06	5.807E-03	4.585E-03	5.87E-04	6.349E-04
2.994	1.408	3.325E+06	4.832E-03	3.668E-03	2.90E-04	8.738E-04
3.992	2.329	4.434E+06	4.494E-03	3.473E-03	1.95E-04	8.261E-04
4.490	2.815	4.987E+06	4.295E-03	3.398E-03	1.62E-04	7.347E-04
4.990	3.471	5.543E+06	4.287E-03	3.333E-03	1.38E-04	8.166E-04
5.488	4.058	6.096E+06	4.144E-03	3.276E-03	1.19E-04	7.498E-04
6.487	5.563	7.205E+06	4.067E-03	3.178E-03	9.60E-05	7.928E-04
7.484	7.390	8.312E+06	4.059E-03	3.099E-03	8.55E-05	8.751E-04
7.984	8.538	8.868E+06	4.120E-03	3.064E-03	8.20E-05	9.746E-04
7.984	8.529	8.868E+06	4.116E-03	3.064E-03	8.20E-05	9.708E-04
8.482	9.729	9.421E+06	4.160E-03	3.031E-03	8.00E-05	1.049E-03

SUBMARINE RESISTANCE
PROGRAM

by

J. V. DE NUTO
MARCH, 1986

NAME OF INPUT DATA FILE:? SUBDAT5

CONSTANT VOLUME W/O TRIP WIRE   11/5/85

MODEL LENGTH = 10.37 ft.
WETTED SURFACE = 29.549 ft^2
APPENDAGE LENGTH = .5 ft.
APPENDAGE WETTED SURFACE = 1.849 ft^2
DENSITY = 1.9367 lb-s^2 / ft^4
KINEMATIC VISCOSITY = 1.0804E-05 ft^2 / s

SPEED (fps)	RESISTANCE (lbs)	Rn	Ct	Cf (ITTC)	Cpara	Cr
0.997	0.103	9.573E+05	3.630E-03	4.732E-03	5.87E-04	-1.689E-03
1.995	0.408	1.915E+06	3.581E-03	4.090E-03	4.20E-04	-9.287E-04
2.993	0.909	2.873E+06	3.546E-03	3.773E-03	2.90E-04	-5.176E-04
3.991	1.626	3.831E+06	3.568E-03	3.570E-03	1.95E-04	-1.976E-04
4.990	2.565	4.789E+06	3.600E-03	3.424E-03	1.38E-04	3.780E-05
4.989	2.536	4.789E+06	3.561E-03	3.424E-03	1.38E-04	-1.145E-06
5.987	3.525	5.746E+06	3.437E-03	3.311E-03	1.05E-04	2.116E-05
5.987	3.514	5.746E+06	3.426E-03	3.311E-03	1.05E-04	1.026E-05
6.985	4.765	6.704E+06	3.414E-03	3.220E-03	9.00E-05	1.038E-04
7.984	6.208	7.663E+06	3.404E-03	3.144E-03	8.20E-05	1.783E-04
8.982	8.408	8.621E+06	3.642E-03	3.079E-03	8.00E-05	4.835E-04

```
**************************************
*                                    *
*      SUBMARINE RESISTANCE          *
*           PROGRAM                  *
*                                    *
*             by                     *
*                                    *
*        J. V. DE NUTO               *
*        MARCH, 1986                 *
*                                    *
**************************************
```

NAME OF INPUT DATA FILE:? SUBDAT6

CONSTANT VOLUME W/TRIP WIRE   11/5/85

MODEL LENGTH = 10.37 ft.
WETTED SURFACE = 29.549 ft^2
APPENDAGE LENGTH = .5 ft.
APPENDAGE WETTED SURFACE = 1.849 ft^2
DENSITY = 1.9367 lb-s^2 / ft^4
KINEMATIC VISCOSITY = 1.0804E-05 ft^2 / s

SPEED (fps)	RESISTANCE (lbs)	Rn	Ct	Cf (ITTC)	Cpara	Cr
0.998	0.166	9.576E+05	5.827E-03	4.732E-03	5.87E-04	5.085E-04
1.995	0.588	1.915E+06	5.160E-03	4.090E-03	4.20E-04	6.499E-04
2.993	1.212	2.873E+06	4.730E-03	3.773E-03	2.90E-04	6.666E-04
3.991	2.043	3.831E+06	4.482E-03	3.570E-03	1.95E-04	7.165E-04
4.989	3.076	4.789E+06	4.319E-03	3.424E-03	1.38E-04	7.570E-04
5.987	4.248	5.746E+06	4.142E-03	3.311E-03	1.05E-04	7.264E-04
6.986	5.703	6.705E+06	4.084E-03	3.220E-03	9.00E-05	7.744E-04
7.984	7.787	7.663E+06	4.269E-03	3.144E-03	8.20E-05	1.044E-03
7.983	7.523	7.662E+06	4.126E-03	3.144E-03	8.20E-05	8.998E-04
8.982	9.853	8.621E+06	4.268E-03	3.079E-03	8.00E-05	1.110E-03

```
****************************************
*                                      *
*        SUBMARINE RESISTANCE          *
*              PROGRAM                 *
*                                      *
*                 by                   *
*                                      *
*           J. V. DE NUTO              *
*            MARCH, 1986               *
*                                      *
****************************************
```

NAME OF INPUT DATA FILE:? SUBDAT7

SHORT BOW W/O TRIP WIRE 11/26/85

MODEL LENGTH = 9.359999 ft.
WETTED SURFACE = 25.95 ft^2
APPENDAGE LENGTH = .5 ft.
APPENDAGE WETTED SURFACE = 1.849 ft^2
DENSITY = 1.9367 lb-s^2 / ft^4
KINEMATIC VISCOSITY = 1.0804E-05 ft^2 / s

SPEED (fps)	RESISTANCE (lbs)	Rn	Ct	Cf (ITTC)	Cpara	Cr
0.998	0.172	8.644E+05	6.870E-03	4.839E-03	5.87E-04	1.444E-03
1.995	0.564	1.729E+06	5.634E-03	4.176E-03	4.20E-04	1.038E-03
2.995	1.133	2.594E+06	5.027E-03	3.849E-03	2.90E-04	8.872E-04
3.993	1.877	3.460E+06	4.685E-03	3.640E-03	1.95E-04	8.492E-04
4.992	2.784	4.325E+06	4.445E-03	3.490E-03	1.38E-04	8.171E-04
5.990	3.865	5.189E+06	4.287E-03	3.373E-03	1.05E-04	8.084E-04
6.987	5.139	6.053E+06	4.189E-03	3.280E-03	9.00E-05	8.197E-04
7.984	6.625	6.917E+06	4.137E-03	3.202E-03	8.20E-05	8.528E-04
7.984	6.469	6.917E+06	4.039E-03	3.202E-03	8.20E-05	7.549E-04
8.981	8.358	7.781E+06	4.123E-03	3.135E-03	8.00E-05	9.081E-04
8.982	8.366	7.781E+06	4.127E-03	3.135E-03	8.00E-05	9.120E-04
8.982	8.511	7.782E+06	4.198E-03	3.135E-03	8.00E-05	9.833E-04
9.977	10.230	8.644E+06	4.090E-03	3.077E-03	8.00E-05	9.323E-04

```
****************************************
*                                      *
*        SUBMARINE RESISTANCE          *
*              PROGRAM                 *
*                                      *
*                 by                   *
*                                      *
*           J. V. DE NUTO              *
*            MARCH, 1986               *
*                                      *
****************************************
```

NAME OF INPUT DATA FILE:? SUBDAT8

SHORT BOW W/TRIP WIRE 11/26/85

MODEL LENGTH = 9.359999 ft.
WETTED SURFACE = 25.95 ft^2
APPENDAGE LENGTH = .5 ft.
APPENDAGE WETTED SURFACE = 1.849 ft^2
DENSITY = 1.9367 lb-s^2 / ft^4
KINEMATIC VISCOSITY = 1.0804E-05 ft^2 / s

SPEED (fps)	RESISTANCE (lbs)	Rn	Ct	Cf (ITTC)	Cpara	Cr
0.998	0.194	8.643E+05	7.744E-03	4.840E-03	5.87E-04	2.317E-03
1.995	0.583	1.728E+06	5.835E-03	4.177E-03	4.20E-04	1.238E-03
2.992	1.177	2.592E+06	5.231E-03	3.850E-03	2.90E-04	1.091E-03
3.992	1.941	3.458E+06	4.847E-03	3.641E-03	1.95E-04	1.012E-03
4.989	2.906	4.323E+06	4.645E-03	3.490E-03	1.38E-04	1.017E-03
5.988	4.034	5.187E+06	4.478E-03	3.374E-03	1.05E-04	9.993E-04
6.985	5.140	6.052E+06	4.192E-03	3.280E-03	9.00E-05	8.223E-04
6.986	5.377	6.052E+06	4.384E-03	3.280E-03	9.00E-05	1.014E-03
7.984	6.675	6.916E+06	4.168E-03	3.202E-03	8.20E-05	8.840E-04
7.981	7.222	6.915E+06	4.512E-03	3.202E-03	8.20E-05	1.228E-03
7.984	7.122	6.917E+06	4.447E-03	3.202E-03	8.20E-05	1.163E-03
8.981	9.249	7.780E+06	4.564E-03	3.135E-03	8.00E-05	1.349E-03
8.980	8.945	7.779E+06	4.415E-03	3.135E-03	8.00E-05	1.200E-03

```
*****************************************
*                                       *
*        SUBMARINE RESISTANCE           *
*              PROGRAM                  *
*                                       *
*                 by                    *
*                                       *
*            J. V. DE NUTO              *
*            MARCH, 1986                *
*                                       *
*****************************************
```

NAME OF INPUT DATA FILE:? SUBDAT9

MEDIUM BOW W/O TRIP WIRE 2/26/86

MODEL LENGTH = 10.66 ft.
WETTED SURFACE = 29.706 ft^2
APPENDAGE LENGTH = .5 ft.
APPENDAGE WETTED SURFACE = 1.849 ft^2
DENSITY = 1.9383 lb-s^2 / ft^4
KINEMATIC VISCOSITY = 1.2083E-05 ft^2 / s

SPEED (fps)	RESISTANCE (lbs)	Rn	Ct	Cf (ITTC)	Cpara	Cr
1.088	0.197	9.597E+05	5.793E-03	4.730E-03	5.87E-04	4.766E-04
2.078	0.686	1.833E+06	5.519E-03	4.127E-03	4.20E-04	9.720E-04
3.069	1.339	2.707E+06	4.940E-03	3.817E-03	2.90E-04	8.323E-04
4.007	2.118	3.535E+06	4.583E-03	3.625E-03	1.95E-04	7.623E-04
5.049	3.181	4.454E+06	4.335E-03	3.470E-03	1.38E-04	7.263E-04
5.067	3.210	4.470E+06	4.342E-03	3.468E-03	1.38E-04	7.357E-04
6.031	4.360	5.321E+06	4.163E-03	3.358E-03	1.05E-04	7.003E-04
6.030	4.354	5.320E+06	4.159E-03	3.358E-03	1.05E-04	6.957E-04
6.996	5.683	6.172E+06	4.033E-03	3.268E-03	9.00E-05	6.746E-04
8.078	7.616	7.126E+06	4.054E-03	3.185E-03	8.20E-05	7.875E-04

SUBMARINE RESISTANCE
PROGRAM

by

J. V. DE NUTO
MARCH, 1986

NAME OF INPUT DATA FILE:? SUBDAT10

MEDIUM BOW W/TRIP WIRE 2/26/85

MODEL LENGTH = 10.66 ft.
WETTED SURFACE = 29.706 ft^2
APPENDAGE LENGTH = .5 ft.
APPENDAGE WETTED SURFACE = 1.849 ft^2
DENSITY = 1.9383 lb-s^2 / ft^4
KINEMATIC VISCOSITY = 1.2083E-05 ft^2 / s

SPEED (fps)	RESISTANCE (lbs)	Rn	Ct	Cf (ITTC)	Cpara	Cr
1.084	0.237	9.566E+05	6.988E-03	4.733E-03	5.87E-04	1.668E-03
2.049	0.681	1.807E+06	5.633E-03	4.138E-03	4.20E-04	1.075E-03
3.015	1.344	2.660E+06	5.136E-03	3.831E-03	2.90E-04	1.016E-03
4.074	2.244	3.594E+06	4.696E-03	3.614E-03	1.95E-04	8.871E-04
5.062	3.319	4.466E+06	4.499E-03	3.469E-03	1.38E-04	8.925E-04
6.029	4.543	5.319E+06	4.342E-03	3.358E-03	1.05E-04	8.783E-04
6.995	5.983	6.171E+06	4.248E-03	3.268E-03	9.00E-05	8.894E-04
8.076	8.053	7.125E+06	4.289E-03	3.185E-03	8.20E-05	1.022E-03

RUN

```
*****************************************
*                                       *
*      SUBMARINE RESISTANCE             *
*            PROGRAM                    *
*                                       *
*              by                       *
*                                       *
*         J. V. DE NUTO                 *
*         MARCH, 1986                   *
*                                       *
*****************************************
```

NAME OF INPUT DATA FILE:? SUBDAT11

CONSTANT LENGTH BOW W/O TRIP WIRE 3/17/86

MODEL LENGTH = 10.66 ft.
WETTED SURFACE = 30.487 ft^2
APPENDAGE LENGTH = .5 ft.
APPENDAGE WETTED SURFACE = 1.849 ft^2
DENSITY = 1.9383 lb-s^2 / ft^4
KINEMATIC.VISCOSITY = 1.2083E-05 ft^2 / s

SPEED (fps)	RESISTANCE (lbs)	Rn	Ct	Cf (ITTC)	Cpara	Cr
2.083	0.481	1.837E+06	3.752E-03	4.125E-03	4.20E-04	-7.927E-04
2.994	0.997	2.642E+06	3.762E-03	3.836E-03	2.90E-04	-3.638E-04
4.028	1.788	3.554E+06	3.731E-03	3.622E-03	1.95E-04	-8.607E-05
5.013	2.789	4.422E+06	3.756E-03	3.475E-03	1.38E-04	1.430E-04
5.998	3.860	5.292E+06	3.631E-03	3.361E-03	1.05E-04	1.643E-04
6.980	5.139	6.158E+06	3.570E-03	3.270E-03	9.00E-05	2.107E-04
7.056	5.352	6.225E+06	3.639E-03	3.263E-03	9.00E-05	2.856E-04
8.040	7.329	7.093E+06	3.838E-03	3.187E-03	8.20E-05	5.683E-04
8.061	7.133	7.111E+06	3.716E-03	3.186E-03	8.20E-05	4.477E-04
8.048	7.092	7.100E+06	3.705E-03	3.187E-03	8.20E-05	4.367E-04
9.054	8.342	7.987E+06	3.444E-03	3.121E-03	8.00E-05	2.437E-04
9.051	9.014	7.985E+06	3.724E-03	3.121E-03	8.00E-05	5.231E-04
9.043	8.799	7.978E+06	3.641E-03	3.121E-03	8.00E-05	4.402E-04

```
*************************************
*                                   *
*       SUBMARINE RESISTANCE        *
*             PROGRAM               *
*                                   *
*                by                 *
*                                   *
*          J. V. DE NUTO            *
*           MARCH, 1986             *
*                                   *
*************************************
```

NAME OF INPUT DATA FILE:? SUBDAT12

CONSTANT LENGTH BOW W/TRIP WIRE   3/17/86

MODEL LENGTH = 10.66 ft.
WETTED SURFACE = 30.487 ft^2
APPENDAGE LENGTH = .5 ft.
APPENDAGE WETTED SURFACE = 1.849 ft^2
DENSITY = 1.9383 lb-s^2 / ft^4
KINEMATIC VISCOSITY = 1.2083E-05 ft^2 / s

SPEED (fps)	RESISTANCE (lbs)	Rn	Ct	Cf (ITTC)	Cpara	Cr
1.090	0.223	9.613E+05	6.350E-03	4.728E-03	5.87E-04	1.035E-03
2.083	0.689	1.837E+06	5.378E-03	4.125E-03	4.20E-04	8.339E-04
3.077	1.401	2.714E+06	5.009E-03	3.815E-03	2.90E-04	9.035E-04
4.067	2.284	3.588E+06	4.672E-03	3.615E-03	1.95E-04	8.620E-04
4.068	2.285	3.588E+06	4.674E-03	3.615E-03	1.95E-04	8.638E-04
5.066	3.380	4.469E+06	4.457E-03	3.468E-03	1.38E-04	8.508E-04
6.056	4.672	5.343E+06	4.312E-03	3.355E-03	1.05E-04	8.517E-04
7.051	6.106	6.220E+06	4.157E-03	3.264E-03	9.00E-05	8.032E-04
8.033	7.667	7.087E+06	4.022E-03	3.188E-03	8.20E-05	7.518E-04
8.030	7.826	7.084E+06	4.107E-03	3.188E-03	8.20E-05	8.374E-04
9.036	8.948	7.972E+06	3.709E-03	3.122E-03	8.00E-05	5.075E-04
9.034	9.871	7.970E+06	4.093E-03	3.122E-03	8.00E-05	8.916E-04
9.029	9.838	7.966E+06	4.084E-03	3.122E-03	8.00E-05	8.820E-04
9.024	9.870	7.962E+06	4.102E-03	3.122E-03	8.00E-05	8.994E-04

APPENDIX D:

NEW WATERLINE SHAPES

PROFILE OFFSETS

```
100 ' GENERATES OFFSETS FOR PROFILE OF FORWARD END OF ARRAY
110 ' NEW BOW SHAPE
120 PRINT "                            PROFILE OFFSETS"
130 PRINT "                             NEW BOW SHAPE" : PRINT
140 G$ =  "                         #.###          #.####"
150 PRINT "                         HEIGHT         LENGTH"
160 PRINT
170 FOR Y=.75 TO 6 STEP .75
180 XSTEP = 1
190 X=1
200 IF X > 4.143 THEN X = X - XSTEP : XSTEP = XSTEP/10
210 Y2=6.375*(1-(X/4.143)^3.79685)^(1/1.732692)
220 IF Y < Y2 THEN X=X + XSTEP : GOTO 200
230 IF XSTEP < .0005 THEN 270
240 X = X - XSTEP
250 XSTEP = XSTEP / 10
260 GOTO 200
270 PRINT USING G$;Y2,X
280 NEXT Y
290 END
```

PROFILE OFFSETS
NEW BOW SHAPE

HEIGHT	LENGTH
0.750	4.1160
1.500	4.0513
2.250	3.9514
3.000	3.8123
3.750	3.6235
4.500	3.3634
5.250	2.9786
6.000	2.2575

WATERLINE OFFSETS

```
100 ' GENERATES OFFSETS FOR WATERLINES
110 ' REVISED BOW
120 G$ =  "                        #.##       #.####"
130 CLS
140 INPUT "                  WATERLINE:";WL
150 INPUT "                  LENGTH :";LFO
160 INPUT "                  BREADTH:";BO
170 LFS = .1
180 LF = LFO
190 X = LF - LFO
200 B = BO : BS = .001
210 Y = B*(1-(X/LF)^3.79685)^.5771366
220 IF Y = BO THEN 260
230 IF Y < BO THEN B = B + BS : GOTO 210
240 IF BS < .00005 THEN 260
250 B = B - BS : BS = BS / 10 : GOTO 210
260  SLOPE   =  B/1.732692*(1-(X/LF)^3.79685)^(-.4228634)*(-
3.79685)*(X/LF)^2.79685
270 IF SLOPE > -.0222397 THEN LF = LF + LFS : GOTO 190
280 IF LFS < .0005 THEN 300
290 LF = LF - LFS : LFS = LFS /10 : GOTO 190
300 PRINT "","   B","   Lf"," SLOPE"
310 PRINT "",B,LF,SLOPE
320 PRINT : PRINT "                      X         Y"
330 FOR X = 0 TO LFO STEP .5
340 Y = B*(1-((X+LF-LFO)/LF)^3.79685)^.5771366
350 PRINT USING G$;X,Y
360 NEXT X
370 END
```

WATERLINE:? 0
LENGTH :? 4.143
BREADTH:? 4.143

B	Lf	SLOPE
4.143691	4.689501	-2.224243E-02

X	Y
0.00	4.1430
0.50	4.1356
1.00	4.1081
1.50	4.0401
2.00	3.9031
2.50	3.6576
3.00	3.2424
3.50	2.5417
4.00	1.1648

WATERLINE:? 0.1.5
LENGTH :? 4.0513
BREADTH:? 4.0050

B	Lf	SLOPE
4.005701	4.593102	-2.224412E-02

X	Y
0.00	4.0050
0.50	3.9974
1.00	3.9689
1.50	3.8982
2.00	3.7554
2.50	3.4984
3.00	3.0604
3.50	2.3077
4.00	0.6406

WATERLINE:? 3.0
LENGTH :? 3.8123
BREADTH:? 3.5567

B	Lf	SLOPE
3.557429	4.347302	-2.224067E-02

X	Y
0.00	3.5567
0.50	3.5486
1.00	3.5178
1.50	3.4410
2.00	3.2849
2.50	3.0003
3.00	2.5036
3.50	1.5854

WATERLINE:? 4.5
LENGTH :? 3.3634
BREADTH:? 2.7506

B	Lf	SLOPE
2.751399	3.887899	-2.224181E-02

X	Y
0.00	2.7506
0.50	2.7413
1.00	2.7057
1.50	2.6156
2.00	2.4293
2.50	2.0775
3.00	1.4023

WATERLINE:? 6.0
LENGTH :? 2.2575
BREADTH:? 1.4180

B	Lf	SLOPE
1.41901	2.722899	-2.224081E-02

X	Y
0.00	1.4180
0.50	1.4030
1.00	1.3395
1.50	1.1645
2.00	0.7275